1985

Sedimentologic and Stratigraphic Significance of Boulder Layers in the Outer Coastal Plain of Southeastern Virginia

Robert C. McDaniel
Old Dominion University

SEDIMENTOLOGIC AND STRATIGRAPHIC SIGNIFICANCE OF BOULDER LAYERS IN THE OUTER COASTAL PLAIN OF SOUTHEASTERN VIRGINIA

by

Robert C. McDaniel
B.S. Geology 1979
Campbell University

A Thesis Submitted to the Faculty of
Old Dominion University in Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE
GEOLOGY

OLD DOMINION UNIVERSITY

Approved by:

Dr. Dennis A. Darby, Director

Dr. Randall Spencer

Dr. Richard Whittecar

ABSTRACT

SEDIMENTOLOGIC AND STRATIGRAPHIC SIGNIFICANCE OF BOULDER LAYERS IN THE OUTER COASTAL PLAIN OF SOUTHEASTERN VIRGINIA

Robert C. McDaniel
Old Dominion University, 1985
Director: Dr. Dennis A. Darby

In southeastern Virginia one to two discontinuous boulder layers occur at the base of the Pleistocene Norfolk Formation. The sediments, heavy minerals and microfossils within the boulder layers in addition to boulder lithologies, dimensions and orientations were studied to determine the origin of these layers. These data indicate the boulder layers were separated into two similar yet distinct layers.

The ancestral James River with sea-level 100 meters lower than today probably had the capacity to entrain 70-80 percent of the clasts in the boulder layers, but probably not the capacity to entrain the larger cobbles and boulders in the boulder layers. Winter river-ice rafting might provide a possible means of transporting the larger and angular clasts from the Blue Ridge and Piedmont Provinces to the boulder layers in southeastern Virginia.

Acknowledgements

I am extremely grateful to Dr. Dennis A. Darby, director of my thesis committee, for his advice and guidance throughout this project. I am indebted to the other members of my committee, Dr. Richard Whittecar and Dr. Randall Spencer, who each contributed to the completion of this study. I also thank Dr. Stephen Culver for his assistance in the identification of the foraminifers.

I wish to express my graditude to Jean Ashmore, Charlie Fox and Linda Ruf who helped me in many ways to complete this study.

Special thanks to my friends and colleagues, Bill Fraser, Al Jasper and Kim Zauderer, for helping in many ways to get this project started and to Mike Babuin, JoAnn Goshorn, Chris Morrell and Yu Wen whose suggestions and advice greatly improved this paper.

Finally, I extend great appreciation to my parents, my brothers and their families for support and encouragement.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

INTRODUCTION

In southeastern Virginia a discontinuous boulder layer occurs at the base of the Pleistocene Norfolk Formation (Darby, 1983). This layer usually consists of a single boulder in thickness associated with medium to coarse sand. The boulders are usually found in a single layer, but in some areas a second stratigraphically higher boulder layer is present, separated from the first by approximately two meters of coarse to medium sand. These boulder layers have been found to exist in all deep pits east of the Suffolk Scarp and from the northern portion of the Hickory Scarp, south to the Albemarle and Chesapeake Canal (Figure 1).

Oaks and Coch (1973) did not report these boulder layers in southeastern Virginia because jet-rig and split-spoon borings used by them could not retrieve cobbles or boulders. Another possible reason the boulder layers were not reported might be due to their depth below the surface, approximately ten to twelve meters (30-36 feet). Sand pits may not have been sufficiently deep to expose the boulders at the time of their study. A less likely possibility is that the boulder layers are sufficiently discontinuous or spacing between boulders are great enough that they were missed by boreholes in this area.

Several possible origins for the boulder layers have

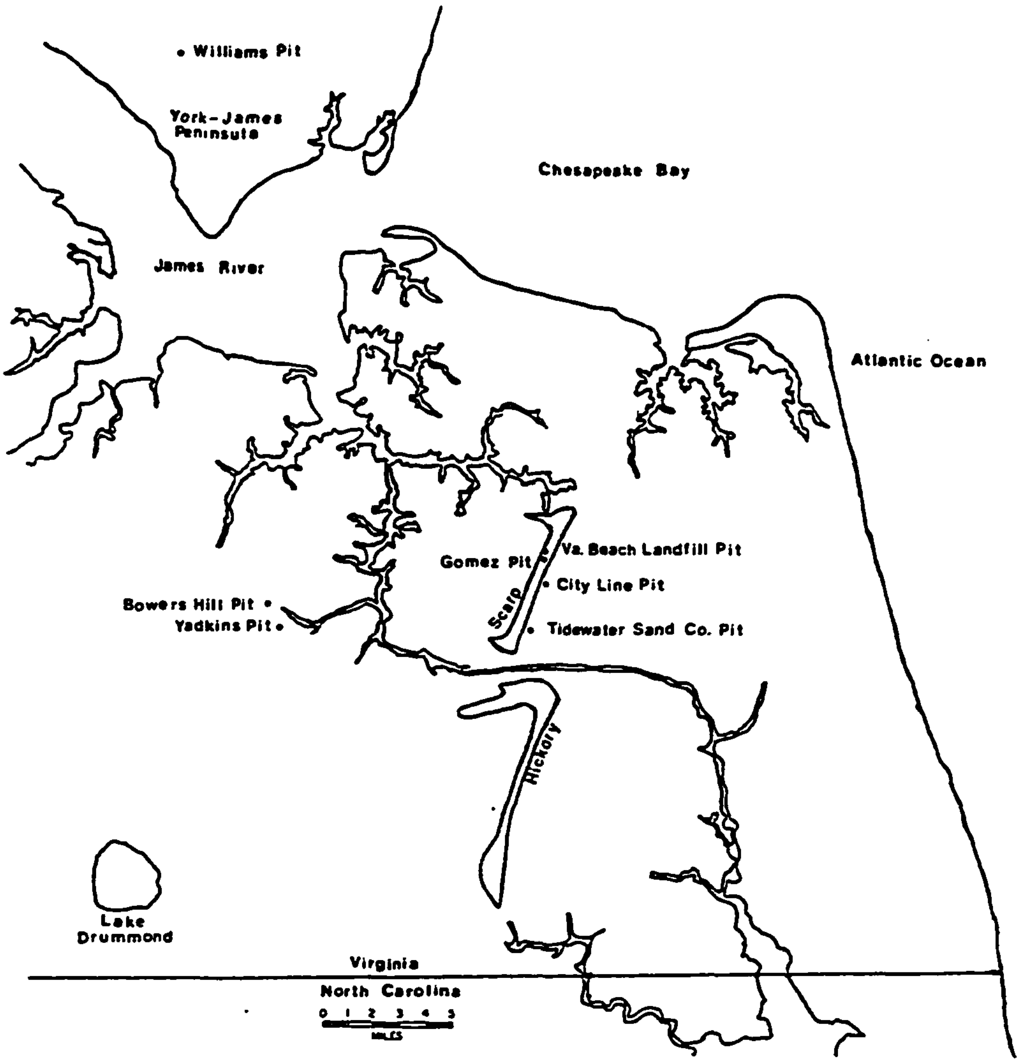


Figure 1. Map of the sand pits which are sufficiently deep to expose the boulder layers in southeastern Virginia. Outline of sand deposits less than a meter below the surface is mapped along the Hickory Scarp (after Oaks and Coch, 1973).

been proposed. Tree-root rafting is one possibility where the boulders are entwined in the roots of trees and floated downstream into a bay (Hanretty, 1974). This process requires a period of high sea-level. Subsequent reworking and winnowing of boulders would leave them in a single layer. Based upon the limited availability of boulders in tree roots along modern river banks, tree-root rafting would probably not result in a large volume of boulders, unless several thousand years of no net deposition occurred. In addition, bay sediments would accumulate during this slow influx of boulders requiring an erosional and winnowing interval to concentrate the boulders into layers.

River ice-rafting during early or late stages of an interglacial high sea-level is a second hypothesis for the boulder layer origin (Darby, 1983). This requires a high sea-level in order to float boulders in the river ice into a bay and distribute them to the areas in which they are presently found. Such a mechanism might result in a wide range of cobble and boulder sizes with a variety of rock types depending upon cobble and boulder availability along the source rivers or estuarine beaches and eroding shorelines. If reworked by storm currents in a bay, the cobbles and most boulders might become oriented.

Wentworth (1930) noted striated quartzite and sandstone cobbles and boulders in the James River Basin (Figure 2). Wentworth found numerous boulders along

Figure 2. Locations along the James River where striated boulders were found (Wentworth, 1930).

Pleistocene terrace deposits of the James River and within 15 miles of the Virginia-North Carolina state line. He suggested that the boulders were transported down the James River by floating ice during a climate cooler than the present (Wentworth, 1927, 1928, 1930). He based this interpretation on striations and boulder distribution and the occasional occurrance of large, at times, fragile boulders.

Emory (1955) listed four major possible sources for beach cobbles and boulders: sea-cliff erosion, stream discharge, sea floor erosion, and long shore transport from any of the preceeding sources. During storms large amounts of sand can be transported seaward (Sanders and Kumar, 1975). Depending on the intensity of the storm, storm-generated currents might not have the capability to remove the coarsest material on the sea floor and thus form a coarse lag deposit (Swift et al., 1969) During a large storm on Fire Island, New York, large quantities of shell and pebbles, with long axes as much as five centimeters in length, were distributed on the foreshore and berm (Sanders and Kumar, 1975). Kumar and Sanders (1976) studied shoreface storm deposits off Fire Island, New York, and noted a basal lag consisting of pebble size or larger material at the bottom of the sequence. This lag is formed during high intensity storms when the finer sediment is kept in suspension while the coarse material concentrates on the sea floor. When the storm wanes the finer sediment is redeposited upon the basal lag (Kumar and Sanders, 1976).

Headland erosion of previously existing fluvial deposits is another possible origin of the boulder layers. A transgressing sea might erode coarse lag material in existing fluvial deposits, distribute and rework the material into a single layer; this process was suggested by Johnson (1981) for the Sedgefield member of the Tabb Formation on the York-James Peninsula.

A final possibility for the origin of the boulder layers might be that streams incised into older formations during a regression. In the succeeding transgression, stream gradients are reduced so that fluvial, paludal, and estuarine deposits fill in the channels. As the sea transgresses landward, it reworks pre-existing deposits into a discontinuous basal lag deposit (Peebles et al., 1984).

The purpose of this study is to determine the depositional and stratigraphic significance of the boulder layers in southeastern Virginia. The previous hypotheses on their origin will be tested in light of new data on the sedimentology and stratigraphy of these boulder layers.

This study is limited to sand pits which are sufficiently deep to expose the boulder layers in southeastern Virginia. The boulder layers are exposed along the Hickory Scarp in the Virginia Beach Landfill Pit, City Line Pit, Tidewater Sand Company Pit, and the

Gomez Pit. Two pits in the Deep Creek Swale were studied, the Yadkins Pit and the Bowers Hill Pit and one pit, the E.V. Williams Pit, along the Big Bethel Scarp (Figure 1).

REGIONAL SETTING

The Outer Coastal Plain east of the Suffolk Scarp was separated into major morphological subdivisions by Oaks and Coch (1973) (Figure 3). These subdivisions from west to east are: the Churchland Flat, the Dismal Swamp, the Deep Creek Swale, the Fentress Rise, the Hickory Scarp, the Mount Pleasant Flat, the Diamond Springs Scarp, the Oceana Ridge and the Sand-Ridge and Mud Flat Complex. Depositional topography is dominant in the areas east of the Suffolk Scarp. Most of the morphological features in this region have a north-south to northeast-southwest trend which is due to the depositional morphology of barrier islands and associated environments (Oaks and Coch, 1973).

The two main morphological subdivisions in which the boulder layers are easily accessible in sand pits are the Deep Creek Swale and the Hickory Scarp. The Deep Creek Swale trends north-south with elevations of 10-15 feet above sea-level. The Hickory Scarp has a northeast-southwest trend with elevations of 20-25 feet.

STRATIGRAPHY

Chowan River Formation

The Chowan River Formation (upper Pliocene) (Blackwelder;

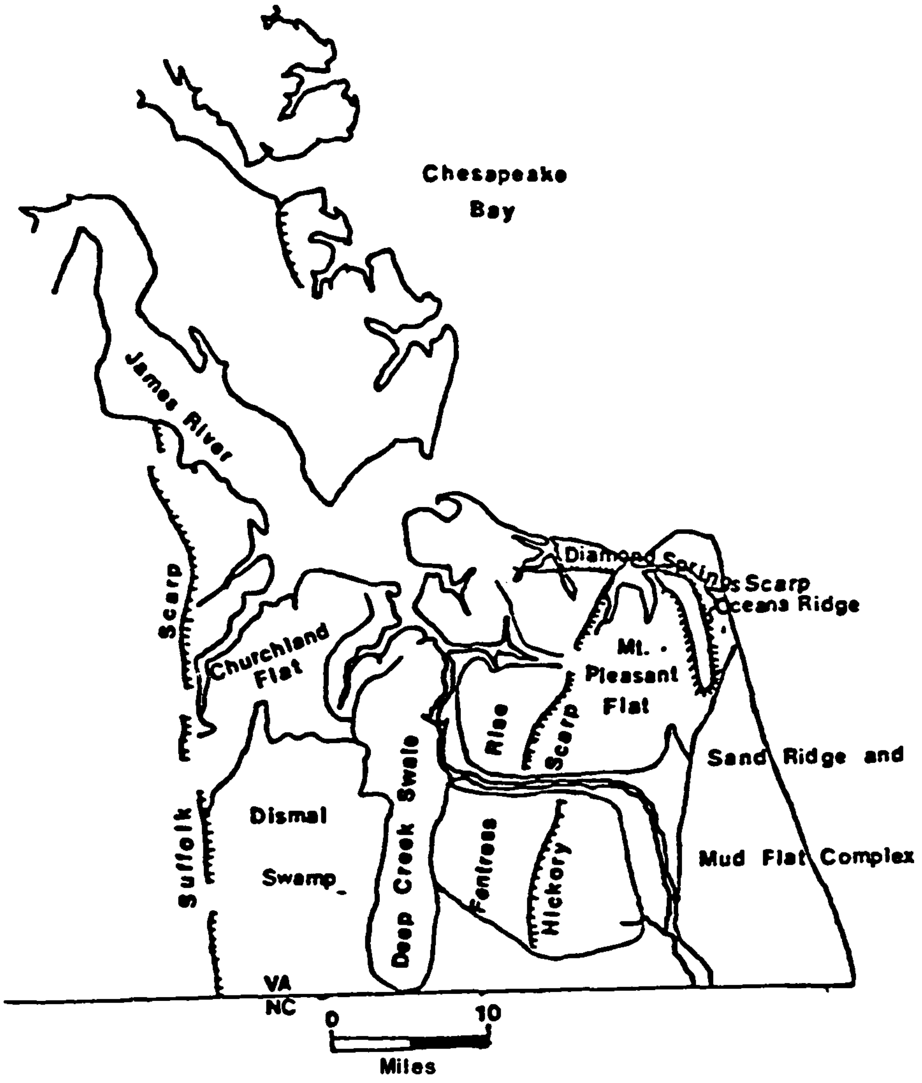


Figure 3. Major morphological subdivisions east of the Suffolk Scarp in southeastern Virginia (after Oaks and Coch,1973).

1981) was first named for deposits of shelly, silty sands and laminated and trough cross-bedded sands and silts along the Chowan River near Colerain Beach, North Carolina. This formation unconformably overlies the Yorktown Formation and was deposited during a global warming event. This event followed global cooling represented by the upper part of the Yorktown Formation and preceded a second cooling event represented by the unconformably overlying James City Formation (Blackwelder, 1981).

The fossiliferous sands and silts of the Chowan River Formation are present in the Gomez Pit. In the northwest part of this pit, typical Chowan River <u>Argopecten</u> and <u>Glycymeris subovata</u> are abundant with some <u>Ostrea</u> and <u>Noetia</u> present. A fossiliferous layer with this fauna is three to five feet thick and extends less than a few hundred feet horizontally in the Gomez Pit. It is leached of all shells elsewhere in the pit. The Chowan River Formation has been previously mapped as the Great Bridge Formation or the Yorktown Formation (Johnson and Peebles,1984).

Norfolk Formation

The Norfolk Formation was named by Clark and Miller (1909) for fossiliferous marine sands and clays which were dredged from the Dismal Swamp Canal. Oaks and Coch (1973) divided this into formations which are in ascending order: Great Bridge, Norfolk, and Kempsville Formations and added two additional stratigraphic units, the Londonbridge and Sand Bridge Formations. The Norfolk Formation was divided into eight different facies composed of sand, silt, and clay deposited in a shallow marine environment, of which only Q_N8, an offshore marine facies, was present in the Hickory Scarp area (Jasper, 1982). Jasper concluded that the Kempsville and Sand Bridge Formations should be reduced to member status within the Norfolk Formation because he recognized a continuous transgressive sequence for sediments previously mapped as Norfolk and Kempsville Formations. The Norfolk Formation represents a transgression-regression cycle in the Sangamon or Mid-Wisconsinan age (Jasper, 1982), possibly correlative with the Sedgefield and Lynnhaven members of the Tabb Formation on the York-James Peninsula (Darby et al., 1984).

Oaks and Coch (1973) gave an approximate age of 62,000 to 86,000 years before present using uranium series dates for the Norfolk Formation. The same method was used by Cronin et al. (1981) and Mixon, Szabo, and Owens (1982) for an estimated age of 72,000-75,000 years and 71,000 ± 7,000 years before present, respectively, for the Norfolk Formation.

FIELD AND LABORATORY PROCEDURES

In an attempt to determine the lithology, surface textures, size, and shape of the boulder layers, 567 boulders were collected in five different sand pits: the Bowers Hill and Yadkins Pits in Deep Creek, Virginia, the Gomez and Virginia Beach Landfill Pits on the Centerville Turnpike in Virginia Beach, Virginia and the City Line Pit on the Kempsville Road in Virginia Beach, Virginia (Figure 1) (Appendix A). In each pit the boulder layer was carefully exposed by a small hand-shovel and when each boulder was encountered, its orientation was measured by a Brunton compass and its lithology noted. When the rock type could not be determined by visual observation, it was studied under binocular microscope in the laboratory and its lithology was confirmed, if necessary, by x-ray diffraction.

A total of 357 long axis orientations and 320 dip directions were measured (Appendix C). The long axis orientations and dip directions were tested for preferred orientations by the chi-squared test (Middleton, 1965; Carver, 1971). The long, intermediate, and short axes of 567 boulders were measured with a Vernier caliper. Maximum projection sphericity (Sneed and Folk, 1958) was then calculated from this data.

One-hundred and eleven samples, 42 from the boulder layers, the rest from adjacent units were taken for laboratory sieve analysis using one-half phi intervals from -2.5 Ø to 4.0 Ø (Folk, 1974). Each sieve fraction was examined by binocular microscope for roundness of the sand grains and percentages of opaque minerals. Statistical size parameters (mean, sorting, skewness, and kurtosis) for each sample were calculated by a sediment analysis computer program (Darby and Wobus, 1976).

Ten samples were analyzed for heavy mineral counts. Three were from a boulder layer at the base of the Sedgefield member of the Tabb Formation (Peebles et al.,1984) in the E.V. Williams Sand Pit along the Big Bethel Scarp on the York-James Peninsula, while seven samples were collected at the base of the Norfolk Formation (Jasper, 1982; Darby, 1983) in the Hickory Scarp area. Of these, three were from a boulder layer between the Chowan River Formation and the Norfolk Formation in the Bowers Hill Pit, two were from the Gomez Pit, and one each from the Yadkins and City Line Pits (Figure 1).

Each sample was dried and sieved with the 2.0 Ø to 4.0 Ø size fractions combined for heavy mineral separation with tetrabromoethane (specific gravity of 2.89). Each sample was randomly split to ten grams with a microsplitter and then placed in a glass tube which was three-quarters filled with tetrabromoethane. The glass tube was placed in a centrifuge for approximately five minutes at a speed of 1000 to 1500 rpm and allowed to stand for two hours. The light and heavy minerals were decanted separately, washed with acetone and dried (Reeves and Brooks, 1978).

Magnetic heavy minerals were separated from non-magnetic heavy mimerals by the use of a hand magnet and the Franz magnetic separator. The non-magnetic fraction was mounted on glass slides with Epofix brand epoxy for microscopic examination. A minimum of 300 non-opaque grains were counted on each slide. The counts were made by successive traverses across the slide and counting each grain which came into the field of view along the center-line (Fleet method).

Forty-one samples from the boulder layers were examined for microfossils. Each sample was wet sieved with a 63 micron sieve to remove silt and clay. The microfossils were separated from the samples by the soap-float method, mounted on a grid slide and identified.

RESULTS

Description of Boulder Layers

One to two discontinuous boulder layers are nearly always present at the base of the Norfolk Formation in the study area east of the Suffolk Scarp (Figure 1). The boulder layers usually consist of clasts of pebble-to-boulder size material in a layer one clast thick. The clasts are not imbricated and rarely are they in contact with each other, though pebbles might be in contact with boulders. In one case, in the City Line Pit, the boulder layer grades into pebbly sands to nearly pure pebble lags up to 0.3 meters (1 foot) thick.

Elevation of Boulder Layers

The boulder layers occur three to five meters (10-16 feet) below sea-level at the Hickory Scarp as measured by transit and alidade. In the northeast corner of the Virginia Beach Landfill Pit (Figure 1) a single boulder layer occurs at 3.1 meters (10.0 feet) below sea-level. In the Gomez Pit, two boulder layers are present. In the northwest portion of this pit a boulder layer occurs at 3.3 meters (10.6 feet) below sea-level and dips eastward so that in the southeastern part of this pit it occurs at 3.4 meters (11.2 feet) below sea-level. Another boulder layer in the Gomez Pit is 4.9 meters (15.9 feet) below sea-level. In the City Line Pit a single boulder layer is found at 4.4 meters (14.3 feet) below sea-level. In the Tidewater Sand Company Pit, a single boulder layer occurs at 7.2 meters (23.5 feet) below sea-level (Jasper, 1982) (Appendix B). In the Bowers Hill Pit a boulder layer is one to two meters (2-6 feet) above sea-level (Darby, 1983). A boulder layer in the Yadkins Pit is found at approximately the same elevation (Appendix B).

A layer of cobbles was found at approximately 6.2 meters (20 feet) below sea-level in the New Light Pit at the base of large scale cross-beds of medium to coarse sands interpreted as tidal channel deposits (Darby, 1983). These tidal channel deposits grade upward to beach sands and washover deposits of a barrier island thought to be correlative with similar beach sands at depths of 1-3 meters in the Gomez and City Line Pits (Darby, 1983; Jasper, 1982).

Sedimentology of Boulder Layers

The upper boulder layer in the Gomez Pit contains coarse to medium sand. The mean grain size is 1.16 ϕ (medium sand) and it is moderately sorted (σ_I = 0.97 ϕ). There are few granule and gravel-size sediments found within the boulder layer. Small pieces of wood fragments may occur occasionally within the layer. The coarse and medium sand grains are usually subrounded and the fine sand is commonly subangular. Rounded mica flakes are generally found with medium and fine sands.

The lower boulder layer in the Gomez Pit is a more discontinuous layer than the upper boulder layer. Sands within the lower boulder layer in the Gomez Pit are medium to fine. Their mean grain size is 1.93 ϕ (medium sand) and they are moderately sorted (σ_I = 0.71 ϕ). Coarse and medium sand grains are usually subrounded and the fine sand is commonly subangular. The lower boulder layer in this pit contains small amounts of rounded mica in the medium and fine sand fractions. Small tree roots and branches along with wood fragments are found in this layer.

A plot of mean grain size verses sorting clusters the upper boulder layer in the Gomez Pit and the boulder layers in the Virginia Beach Landfill and City Line Pits separate from the lower boulder layer in the Gomez Pit and the boulder layers in the Bowers Hill Pit and the Yadkins Pit (Figure 4). The primary difference between these groups is mean grain size, with the latter group being finer grained. The same relationship was found for mean grain size and skewness (Figure 5). Sorting and skewness are similar throughout and not useful for distinguishing the boulder layers (Figure 6). The same is true for kurtosis (Figure 7).

Using the weight percent of each half phi fraction, a principal component analysis (Figure 8) and cluster analysis (Davis, 1973) (Figure 9) showed the same separation as the mean size plots. The upper boulder layer in the Gomez Pit and the boulder layers in the Virginia Beach Landfill and City Line Pits grouped together due to a higher percentage of coarse material in these samples.

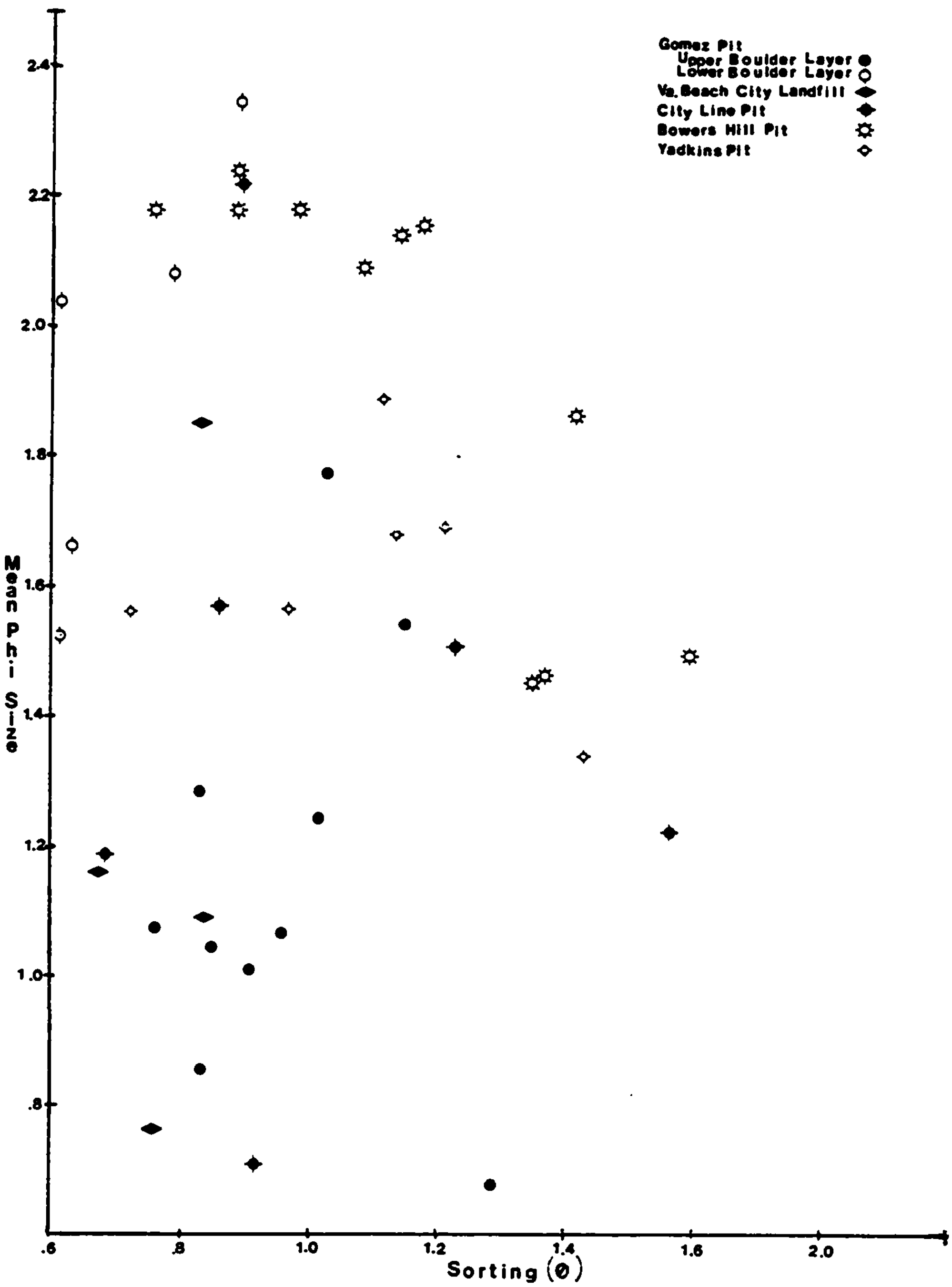


Figure 4. Plot of mean grain size verses sorting for the sands within the boulder layers in southeastern Virginia.

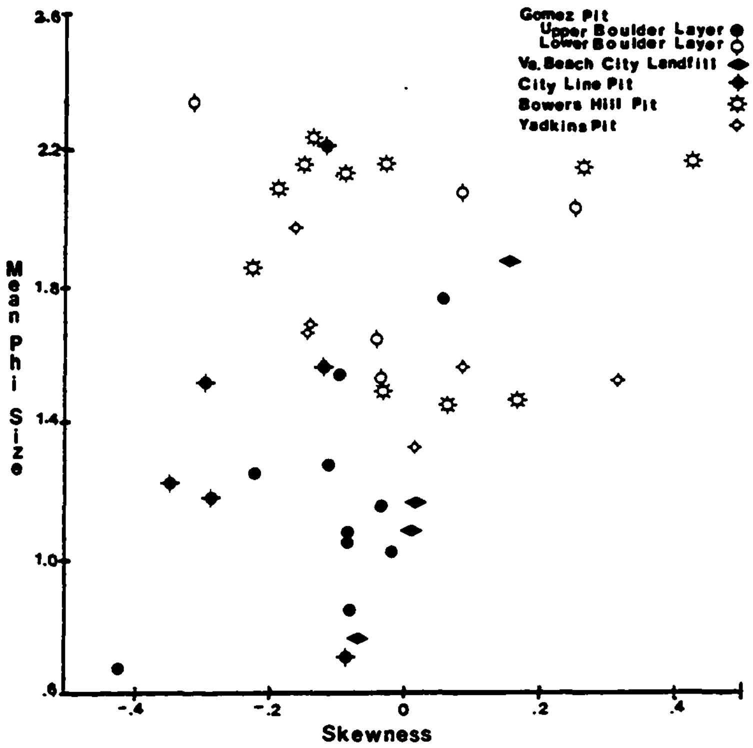


Figure 5. Plot of mean grain size verses skewness of the sands within the boulder layers.

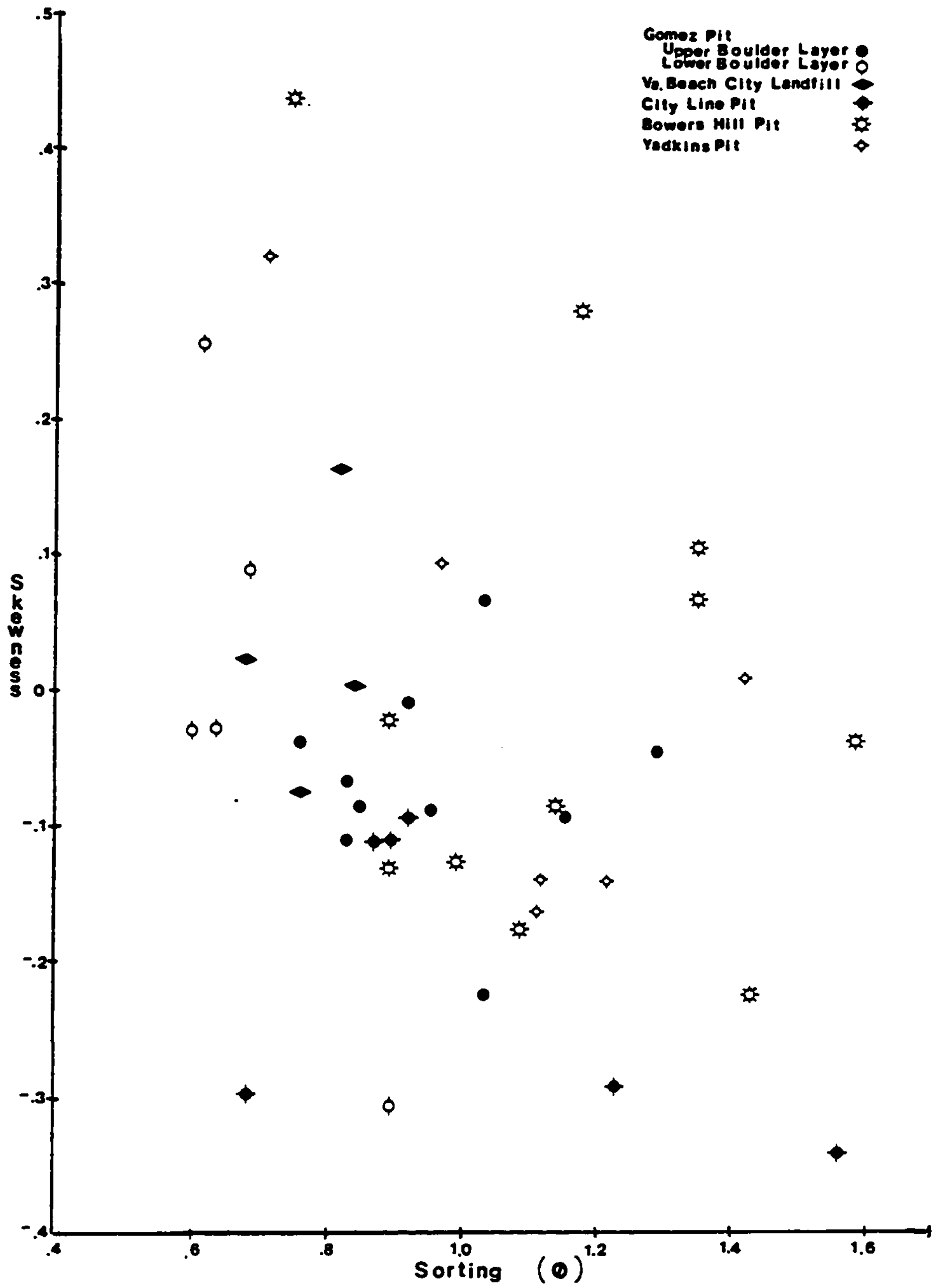


Figure 6 . Plot of skewness verses sorting of the sands within the boulder layers.

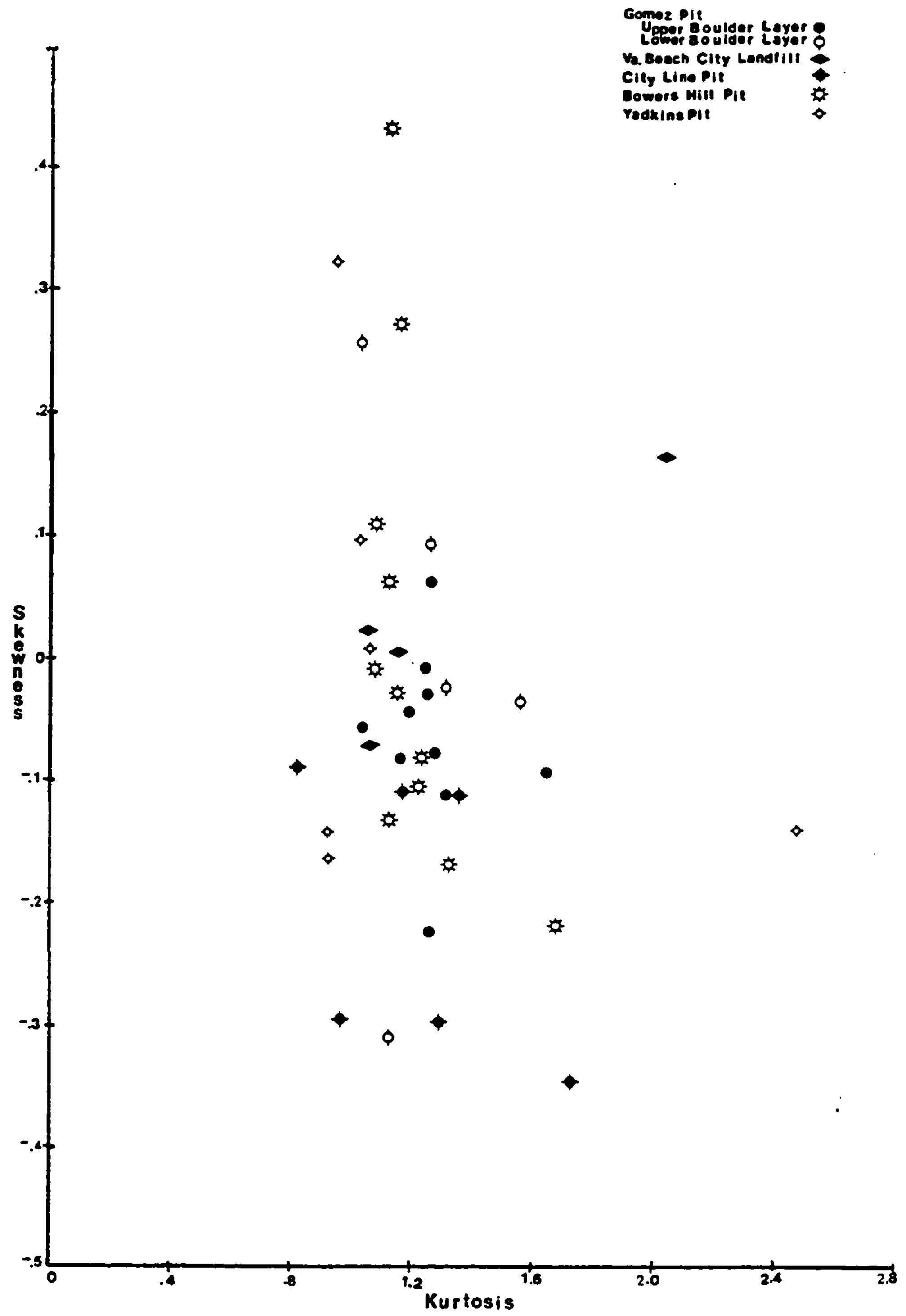


Figure 7. Plot of skewness verses kurtosis of the sands within the boulder layers.

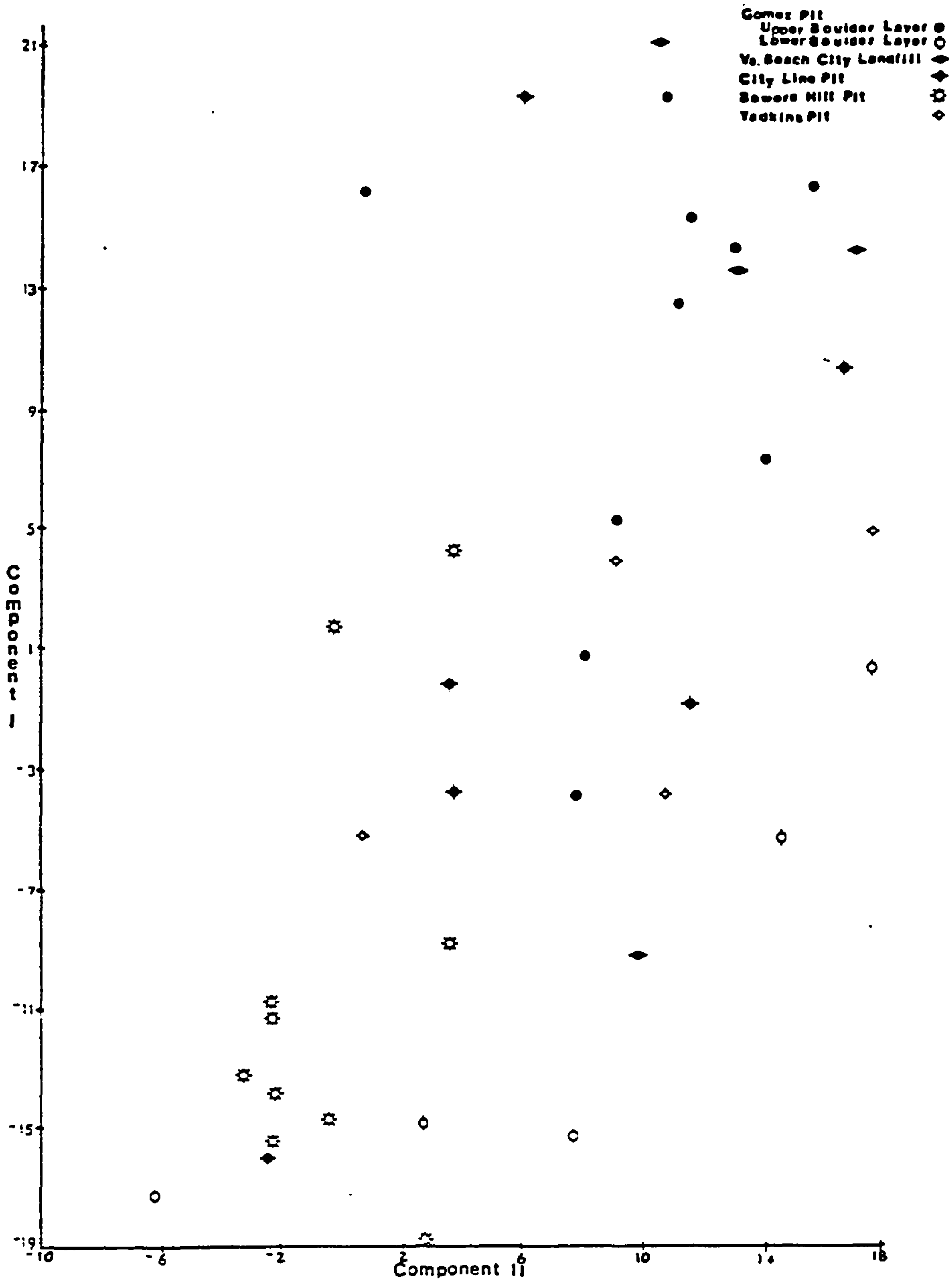


Figure 8. Principal component analysis of the sands within the boulder layers in southeastern Virginia.

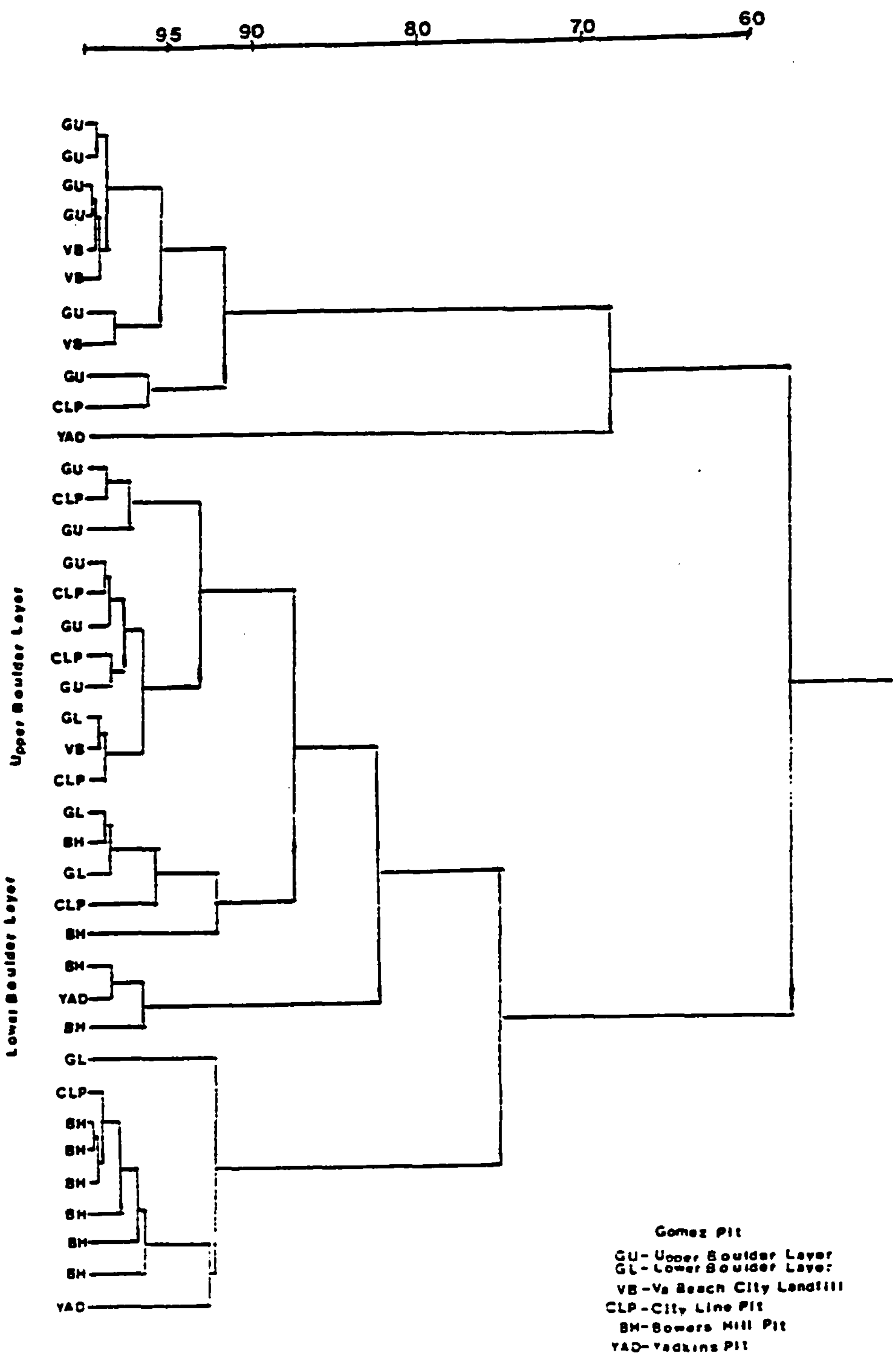


Figure 9 . Cluster dendrogram of one-half phi fractions of the sands within the boulder layers in southeastern Virginia.

In the Gomez Pit the lower boulder layer is restricted to a paleochannel in the southern end of the pit. Four traverses were made by a hand auger, 105 to 117 meters (340 to 380 feet) apart, to construct a profile of the channel. The deepest part of the channel measured was 4.6 meters (15 feet). The lower boulder layer occurs at the top of the channel (Figure 10).

Tree stumps in life position overlie the lower boulder layer in the Gomez Pit (Figure 10) with their roots entwined around the boulders. Usually the stumps are encased with mud, thus helping to preserve them. Cyprus, gum, and pine are the most common stumps found above the boulders.

The channel deposit below the lower boulder layer in the Gomez Pit is a compact, fine sand. The mean grain size is 2.78 ϕ (fine sand) and the sand is moderately sorted (σ_I = 0.79 ϕ). The coarse sand fractions within the channel deposit are usually subrounded while the fine fractions are subangular. Rounded mica is usually found in the coarse and medium sand size fractions. The sands are glauconite-free but are usually green to greenish-blue in color.

The sands beneath the channel are very similar, in texture, to the sands within the channel. Because of this similarity the channel-filling sediments below the lower boulder layer are grouped with the Chowan River Formation. The sands beneath the channel are dark grey to black and are very compact. The mean grain size of this sand is 2.64 ϕ (fine sand) and it is moderately sorted (σ_I = 0.82 ϕ).

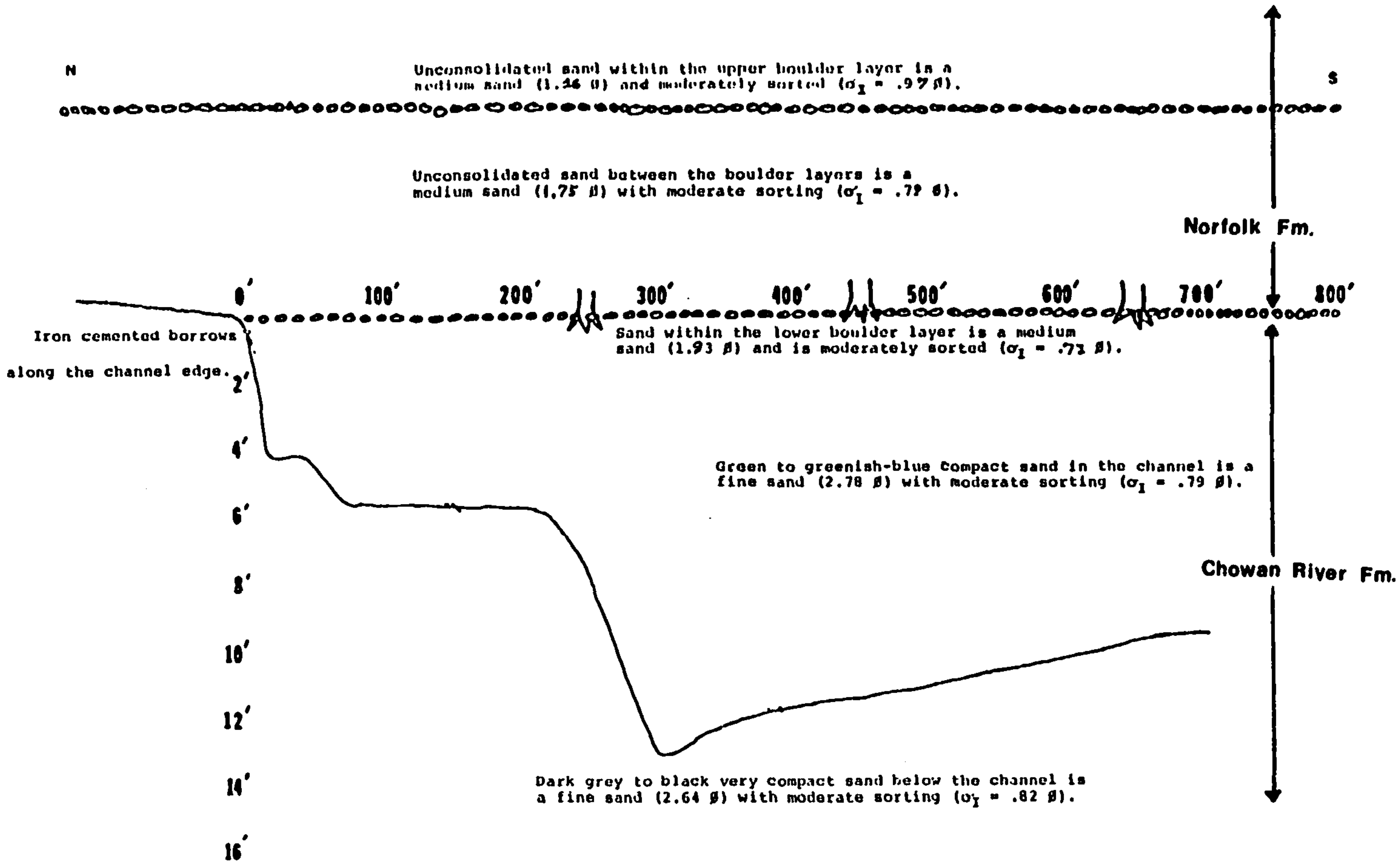


Figure 10. The lower boulder layer with tree stumps in life position overlying a channel deposit in the Gomez Pit. The upper boulder layer is approximately two meters above the lower boulder layer in this Pit.

Microfossils

Benthic foraminifers were found in six of the forty-one samples examined from the boulder layers in southeastern Virginia (Table 1). The genus Elphidium dominated samples from both boulder layers in the Gomez Pit and a boulder layer in the Yadkins Pit. Elphidium accounts for 74 to 92 percent of the foraminifers in these samples. The genus Ammonia usually is the second most abundant, accounting for 5.9 to 17.0 % of the foraminifers. Other genera in the boulder layers include Buccella, Cibicides, Globorotalia, Haynesina, Nonion, Nonionella, Poroeponides, Quinqueloculina, and Rosalina.

Boulder Lithologies

Nine different boulder lithologies have been identified. They are in order of decreasing abundance: quartzite, sandstone, granite, schist, mudballs, gneiss, unakite, siltstone, and greenstone (Table 2). Quartzite was always the dominant rock type, averaging 78 percent of the boulders. In the two western most pits (Bowers Hill and Yadkins Pits), quartzite comprised 82 ± 4 percent of the rock types while only making up 69 ± 3 percent of the rock types in the lower boulder layer of the Gomez Pit 16 kilometers (10 miles) to the east. Quartzite composed only 26 ± 4 percent of the rock types in the James River, five kilometers west of Richmond, Virginia (Table 3). The boulder count was made in the James River due to the close proximity of the mouth of this river to the boulder layer deposits in southeastern

Table 1. Percentage of foraminifers found in the lower boulder layer in the Gomez Pit (G-LBL), the upper boulder layer in the Gomez Pit (G-UBL), and the boulder layer in the Yadkins Pit (YAD).

Genera	G-LBL	G-LBL	YAD	G-UBL	G-UBL	G-UBL
Ammonia	10.8	9.2	9.3	12.0	10.0	7.9
Buccella	2.7	1.7	1.8	-	1.3	2.6
Cibicides	-	-	-	1.0	1.3	1.3
Elphidium	78.4	80.7	78.7	76.0	77.5	76.3
Globorotalia	0.9	-	-	-	-	-
Haynesina	0.9	0.8	0.9	2.0	1.3	-
Nonion	-	2.5	1.8	3.0	1.3	1.3
Nonionella	0.9	0.8	2.8	-	-	2.6
Poroeponides	-	-	-	1.0	1.3	-
Quinqueloculina	1.8	0.8	1.8	3.0	2.5	2.6
Rosalina	3.6	3.4	2.8	2.0	3.7	5.3

Table 2. Percentage of rock types within the boulder layers in each pit.

Rock Type	Gomez - Upper Boulder Layer	Gomez - Lower Boulder Layer	City Line Pit	VA.Beach Landfill	Bowers Hill	Yadkins Pit
Quartzite	79.5 ±2.1	69.2 ±4.5	80.9 ±4.5	74.0 ±6.5	82.3 ±5.5	82.0 ±6.5
Sandstone	5.4 ±1.3	9.6 ±2.9	8.3 ±3.4	6.0 ±3.2	3.9 ±2.9	5.1 ±3.4
Siltstone	1.3	1.9 ±1.3	-	4.0 ±2.9	-	-
Granite	5.9 ±1.3	7.7 ±2.4	3.6 ±1.7	8.0 ±3.6	2.0 ±1.7	2.6 ±2.2
Schist	4.2 ±1.2	5.8 ±2.2	2.4 ±1.4	4.0 ±2.9	2.0 ±1.7	-
Gneiss	2.1 ±0.8	2.9 ±1.4	2.4 ±1.4	2.0 ±1.7	2.0 ±1.7	2.6 ±2.2
Mudball	-	-	-	-	7.8 ±3.6	7.7 ±3.8
Greenstone	0.4	1.0	-	-	-	-
Unakite	1.2	1.9 ±1.3	2.4 ±1.4	2.0 ±1.7	-	-
Total Count	239	104	84	50	51	39

Table 3. Number and percentage of rock types found in the James River, five kilometers upstream from Richmond, Virginia.

Rock Type	Number of Rock Type counted	Percentage of Rock Type
Sandstone	53	54.6 ±4.8
Quartzite	25	25.8 ±4.3
Gneiss	7	7.2 ±2.4
Anorthosite	4	4.1 ±1.9
Basalt	2	2.1 ±1.3
Arkose	1	1.0
Granite	1	1.0
Chert	1	1.0
Unakite	1	1.0
Pegmatite	1	1.0
Limestone	1	1.0

Virginia and the fact that the river drains the Piedmont, Blue Ridge, and Valley and Ridge Provinces in areas which are likely sources for these rock types (Milici et al.,1963).

Sandstone was the second most abundant rock type identified in the boulder layers, averaging 6.4 ± 0.9 percent of the total. It was the dominant lithology in the James River, comprising 54.0 ± 5 percent of the boulders (Table 3).

Granite accounted for 4.9 ± 0.9 percent of the boulders collected in the sand pits. In the James River, granite only comprised one percent of the rock types.

Mudballs were found only in the western most pits in the study area, the Bowers Hill and Yadkins Pits. Mudballs comprised 8.0 ± 1.1 percent of the rock types in these pits.

Unakite comprised 1.9 percent of the rock types in the boulder layers. Unakite is a granitic rock containing orthoclase, green epidote, and blue-gray quartz (Allen, 1967). Unakite is usually associated with the Pedlar Formation and near the contact of the Virginia Blue Ridge complex and the Catoctin Formation when granodiorite is close to the greenstone of the Catoctin Formation (Nelson, 1962).

Boulder Dimensions

The average long, intermediate, and short axes of the clasts within the boulder layers were approximately the same in each pit (Table 4). These average dimensions can not be used to separate the boulder layers because of the large variance of the dimensions. Some large boulders have been found with long axes of up to 2.5 meters in length (Darby, 1983). The largest boulders are commonly granites, but quartzites with long axis lengths of 15-20 centimeters are not unusual.

The maximum projection sphericity values (Folk, 1974) of the boulders were also similar in all of the boulder layer deposits. The average values ranged from 0.64 ± 0.11 in the Virginia Beach Landfill Pit to 0.70 ± 0.11 in the upper boulder layer in the Gomez Pit (Table 4). Sphericity is strongly influenced by the composition of the original source rock. The average sphericity value of quartzite clasts in the boulder layers is 0.67 whereas the average value of granite and sandstone is 0.65 and 0.62, respectively. The degree of sphericity might increase with increasing transportation and time in which the rock is subjected to abrasion (Reineck and Singh, 1975).

Boulder Orientations

The long axis orientations and dip directions vary from pit to pit (Table 5). The long axis orientations in the Virginia Beach Landfill Pit, the Bowers Hill Pit, and the lower boulder layer in the Gomez Pit had random orientations. Using a chi-squared test for preferred

Table 4. Average boulder dimensions and sphericity.

Location	Long Axis	Intermediate Axis	Short Axis	Sphericity
Gomez - Upper Boulder Layer (n = 239)	7.37 cm ±3.3	5.47 cm ±2.1	3.55 cm ±0.8	0.70 ±0.11
VA.Beach Landfill (n = 50)	6.65 ±3.2	5.06 ±2.8	2.99 ±1.1	0.65 ±0.11
City Line Pit (n = 84)	9.48 ±4.8	6.93 ±3.9	4.30 ±1.9	0.67 ±0.12
Gomez - Lower Boulder Layer (n = 104)	7.23 ±4.3	5.57 ±3.0	3.50 ±1.4	0.65 ±0.13
Bowers Hill Pit (n = 51)	9.85 ±4.5	6.86 ±2.8	4.22 ±1.5	0.65 ±0.13
Yadkins Pit (n = 39)	7.31 ±2.9	5.25 ±2.1	3.44 ±0.9	0.69 ±0.12

TABLE 5. Preferred orientation of the long axis and dip direction of the boulders within the boulder layers in southeastern Virginia.

Location	Long Axis Preferred Orientation	Dip Direction Preferred Orientation
Gomez - Upper Boulder Layer	165.4 °	193.5 °
VA. Beach Landfill	Random	356.4
City Line Pit	129.9	222.6
Gomez - Lower Boulder Layer	Random	185.1
Bowers Hill Pit	Random	97.4
Yadkins Pit	100.7	Random

orientations, the long axis orientations of the upper boulder layer in the Gomez Pit (165.4°) and the City Line Pit (129.9°) showed a northwest-southeast trend (Figure 11). The long axis in the Yadkins Pit has nearly an east-west orientation (100°).

The preferred orientation of the dip directions vary from pit to pit (Table 5). The dip directions of the boulder layer in the Virginia Beach Landfill Pit, the City Line Pit, and the upper boulder layer in the Gomez Pit indicate a northern, southwestern, and southern orientation, respectively (Figure 12). The boulder layer in the Bowers Hill Pit and the lower boulder layer in the Gomez Pit show a preferred orientation to the east and south (Figure 12). Yadkins Pit was the only location which did not have a preferred orientation for the dip directions.

Heavy Minerals

The identification of heavy minerals in five sand pits in southeastern Virginia provides information about the provenance of the sands within the boulder layers. Non-opaque heavy minerals were studied in all ten samples collected from the boulder layers. Three samples from a boulder layer at the base of the Sedgefield member of the Tabb Formation (Peebles et al., 1984) (Table 6) in the E.V. Williams Pit along the Big Bethel Scarp on the York-James Peninsula. Seven samples from the base of the Norfolk Formation (Jasper, 1982; Darby, 1983), three samples from

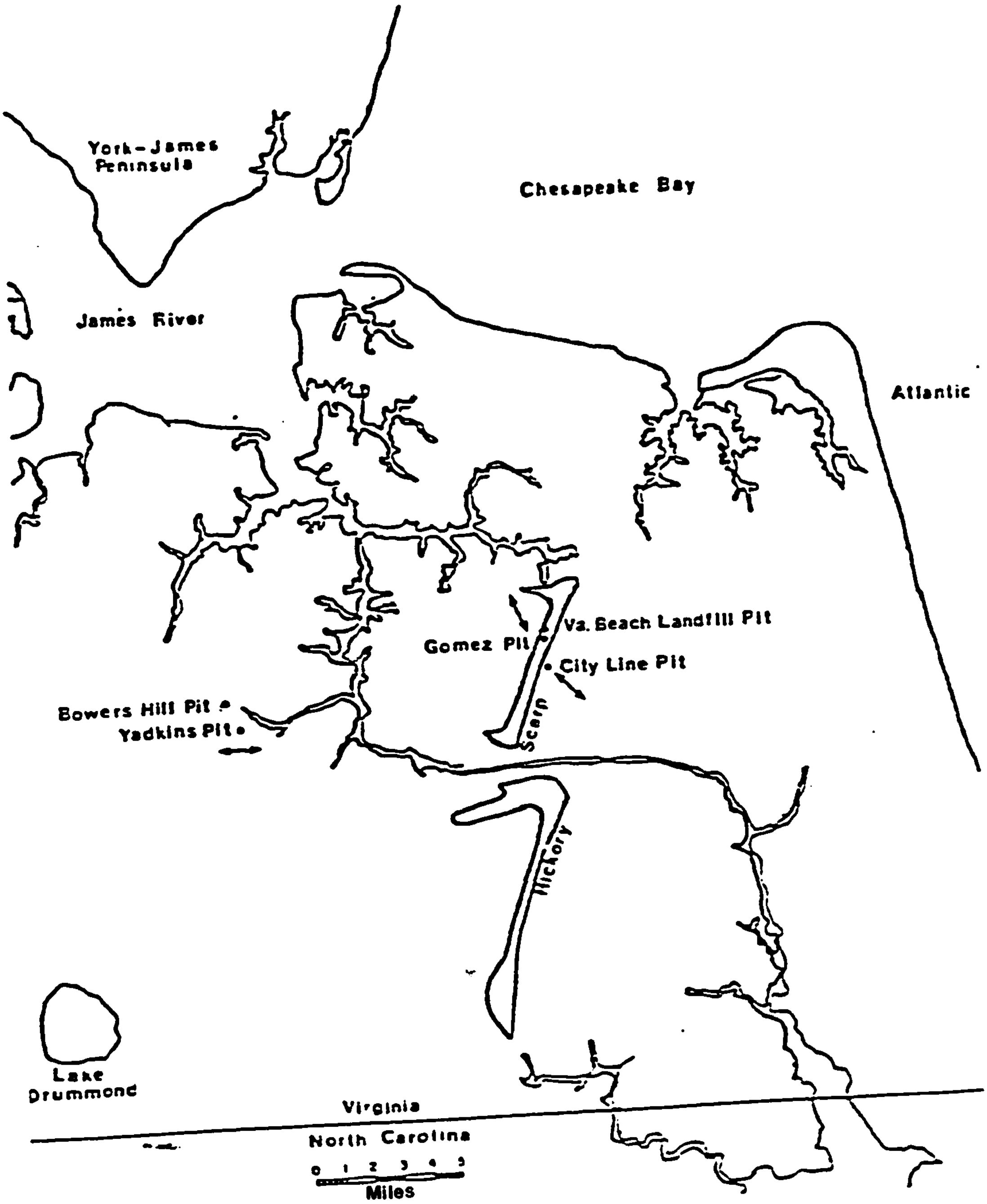


Figure 11. Long axis orientations of the boulder layers in the Yadkins Pit, City Line Pit, and the upper boulder layer in the Gomez Pit.

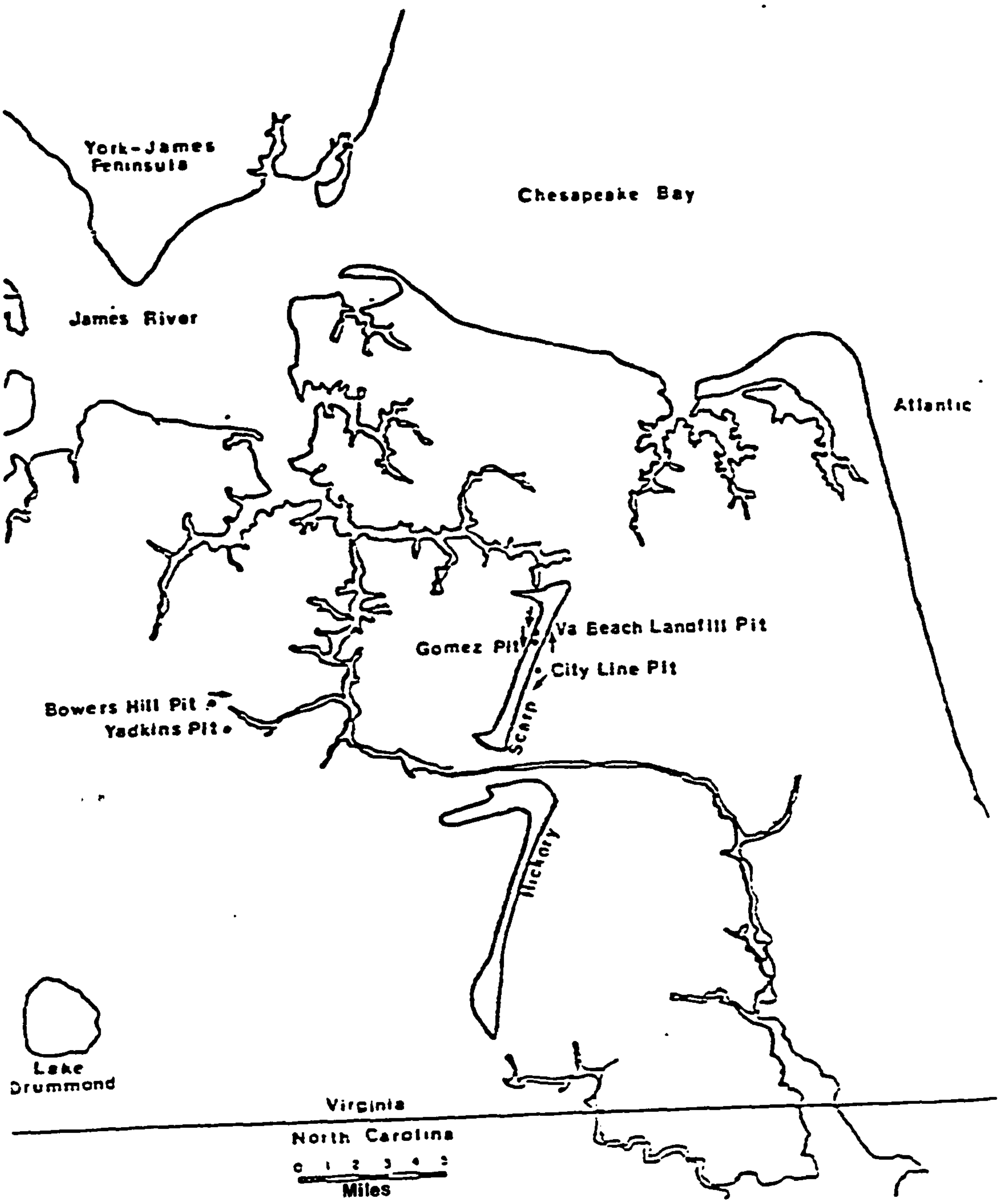


Figure 12. Dip directions of the upper boulder layer in the Gomez Pit, Virginia Beach Landfill Pit, City Line Pit, Bowers Hill Pit, and the lower boulder layer in the Gomez Pit.

Series	Peebles et al.	Darby (1983)	Mixon, Szabo and Owens (1982)	Johnson (1976) Johnson, Berquist, Ramsey and Peebles (1981)	Oaks and Coch (1973) Coch(1968,1971)
Upper Pleistocene	Tabb Fm., Poquoson Mbr.	Not covered in report	Sand Bridge Fm.*	Tabb Fm., Poquoson Mbr.	Sand Bridge Fm.*
	Tabb Fm., Lynnhaven Mbr.	Norfolk Fm. (Upper Pleistocene)	Sand Bridge Fm.* Kempsville Fm.*	Tabb Fm., Lynnhaven Mbr.	Sand Bridge Fm.* Kempsville Fm.* Norfolk Fm.*
	Tabb Fm., Sedgefield Mbr.		Kempsville Fm.* Norfolk Fm. (type area)	Tabb Fm., Sedgefield Mbr.	Sand Bridge Fm.* Kempsville Fm.* Londonbridge Fm.* Norfolk Fm.* Great Bridge Fm.*
Middle Pleistocene	Shirley Fm.	Not present	Norfolk Fm. (West of Suffolk scarp) (Upper Pleistocene)	Norfolk Fm. (Upper Pleistocene)	Norfolk Fm. (clayey sand facies)
Upper Pliocene	Chowan River Fm.	Great Bridge Fm. (Upper ? Pleistocene)	Great Bridge Fm. (Upper Pleistocene)	Not present	Great Bridge Fm.* (Upper Pleistocene)

* In part

Table 6. Comparison of stratigraphic units in southeastern Virginia (Peebles et al., 1984).

the Bowers Hill Pit, one sample each from the Yadkins Pit, the City Line Pit, the upper boulder layer in the Gomez Pit, and the lower boulder layer in the Gomez Pit (Table 7).

While opaque minerals (mostly ilmenite) made up 40-50 percent of the heavy mineral fraction in these pits (Darby, unpublished data), hornblende and epidote were the dominant minerals of the non-opaque fraction, usually accounting for 60-70 percent. Garnet, kyanite, zircon, tourmaline, spinel, and wollastonite were found to vary in the different pits. Rutile was in small amounts only in the boulder layer along the Big Bethel Scarp and augite was found only in the boulder layer in the Bowers Hill Pit.

Cluster analysis (Davis, 1973) of the non-opaque heavy minerals counts from the sands within the boulder layers grouped the samples into three groups: 1) the three samples from the base of the Sedgefield member of the Tabb Formation along the Big Bethel Scarp; 2) the samples from the boulder layers at the base of the Norfolk Formation in the Bowers Hill Pit, Yadkins Pit, and the lower boulder layer in the Gomez Pit; and 3) samples from the boulder layers at the base of the Norfolk Formation in the City Line Pit and the upper boulder layer in the Gomez Pit (Figure 13). The second and third groups are same groups separated using sediment textures (Figure 9).

The heavy mineral suite from the base of the Sedgefield member of the Tabb Formation along the Big Bethel Scarp differs from the other groups in several ways. The

Table 7. Percentage of heavy minerals in the Big Bethel Scarp (BBS), the Bowers Hill Pit (BH), Yadkins Pit (YAD), Gomez Pit (lower, GL and upper, GU, boulder layers), and the City Line Pit (CLP).

Mineral	BBS-1	BBS-2	BBS-3	BH-1	BH-2	BH-3	YAD	GL	GU	CLP
Hornblende	39.5 ±2.8	47.0 ±2.7	48.9 ±2.9	48.4 ±2.7	40.6 ±2.8	45.6 ±2.8	49.4 ±2.6	46.5 ±2.8	47.4 ±2.8	45.4 ±2.7
Epidote	30.4 ±2.6	27.0 ±2.4	24.3 ±2.2	30.0 ±2.4	30.3 ±2.6	24.8 ±2.4	28.3 ±2.3	28.9 ±2.6	20.8 ±2.1	23.9 ±2.1
Garnet	3.8 ±1.1	4.9 ±1.1	3.5 ±1.0	8.8 ±1.4	10.9 ±1.6	16.8 ±2.2	12.1 ±1.6	9.2 ±1.2	10.2 ±1.6	10.1 ±1.6
Kyanite	7.7 ±1.5	3.9 ±1.0	4.4 ±1.1	5.4 ±1.1	7.8 ±1.4	4.3 ±1.1	2.2 ±0.7	8.9 ±1.1	12.0 ±1.7	8.9 ±1.3
Tourmaline	1.8	3.4 ±0.9	3.2 ±1.0	2.3 ±0.7	1.8	0.6	1.1	2.5 ±0.7	5.0 ±1.1	5.6 ±1.2
Zircon	2.1 ±0.7	3.1 ±0.9	1.9	1.1	3.9 ±1.0	1.9	1.9	1.3	0.9	1.1
Spinel	0.6	0.6	0.6	0.3	2.1 ±0.7	0.9	1.1	0.3	0.9	0.9
Wollastonite	1.2	1.1	0.9	2.0 ±0.7	1.5	2.2	1.6	1.6	1.7	2.4 ±0.7
Sphene	9.4 ±1.7	6.8 ±1.2	9.5 ±1.5	0.3	0.0	1.2	0.3	0.3	0.3	0.0
Andalusite	0.9	0.6	0.6	0.8	0.0	0.9	0.8	0.0	0.9	1.2
Apatite	1.5	0.8	0.9	0.6	0.0	0.6	1.1	0.3	0.0	0.6
Rutile	1.2	0.8	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Augite	0.0	0.0	0.0	0.0	0.9	0.0	0.0	0.0	0.0	0.0
Total Counts	339	355	317	353	331	322	364	309	342	335

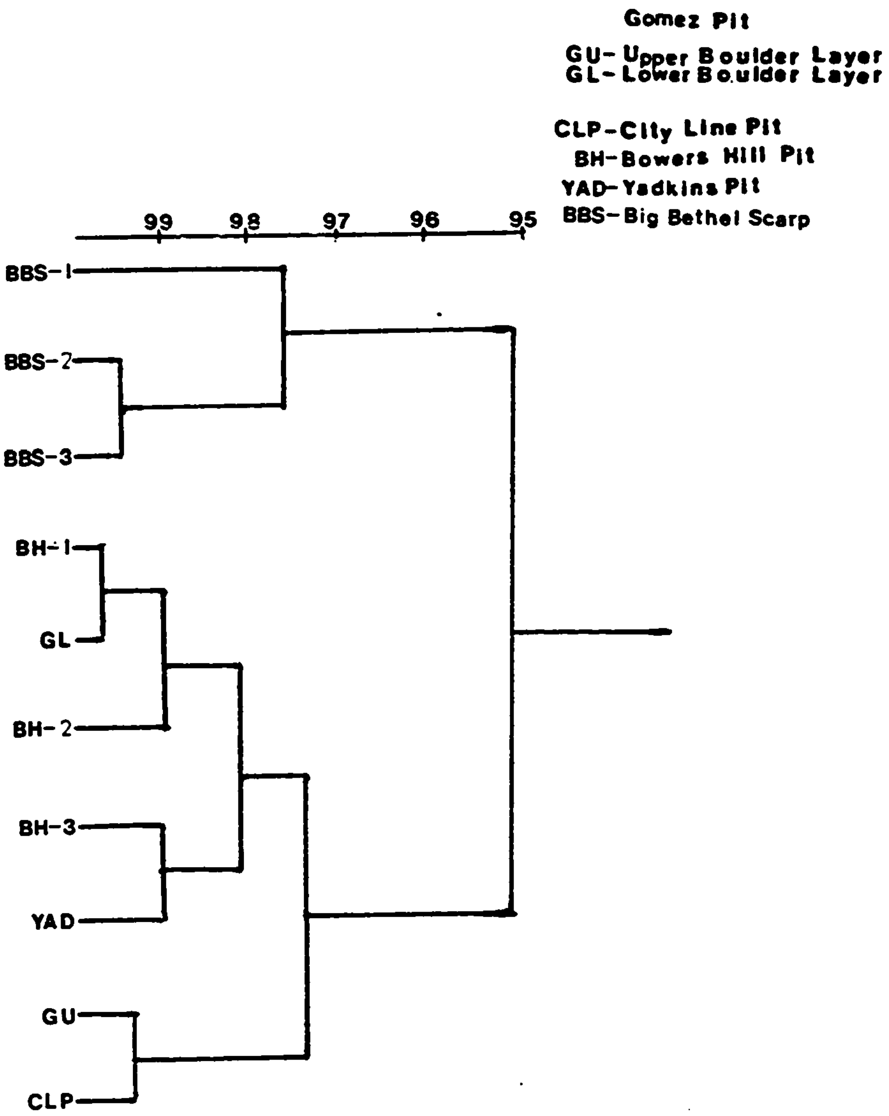


Figure 13. Cluster dendrogram of the heavy minerals found in the boulder layers. Three groups are recognized: the Big Bethel Scarp group (BBS), group two (BH, GL, YAD), and group three (GU,CLP).

percentage of garnet was lower in the Big Bethel Scarp samples (Table 8). While sphene accounted for 8.6 $\pm$ 0.8 percent of the heavy minerals in this sample group, but was only 0.4 or 0.2 percent in the other two groups from the boulder layers at the base of the Norfolk Formation. The Big Bethel Scarp samples also had slightly more spinel, wollastonite, and apatite than the other two groups. Rutile was found only in the Big Bethel Scarp samples and was absent in the other boulder layers.

Group two (BH, GL, YAD) has slightly more epidote (28.5 $\pm$ 1.1) than group three (GU, CLP) (22.3 $\pm$ 1.6). Group two also has a higher percentage of garnet, zircon, sphene, and apatite compared to group three. Augite was found only in the Bowers Hill Pit in group two. Group three had considerably more kyanite and tourmaline than the other groups. This group also had slightly higher percentages of hornblende, wollastonite, and andalusite than was found in the boulder layers in the second group.

Table 8. Average heavy mineral percentages of the three groups separated by the cluster analysis: the Big Bethel Scarp group (BBS), group two (BH, GL, YAD), and group three (GU, CLP).

Mineral	Big Bethel Scarp	Group Two	Group Three
Hornblende	45.2 ±1.5	46.1 ±1.2	46.4 ±1.9
Epidote	27.2 ±1.2	28.5 ±1.1	22.3 ±1.6
Garnet	4.1 ±0.6	11.6 ±0.8	10.1 ±1.0
Kyanite	5.3 ±0.7	5.7 ±0.6	10.4 ±1.0
Tourmaline	2.4 ±0.4	1.7	5.3 ±0.8
Zircon	0.6	2.0 ±0.3	1.0
Spinel	1.1	0.9	0.9
Wollastonite	2.8 ±0.4	1.8	2.1 ±0.4
Sphene	8.6 ±0.8	0.4	0.2
Andalusite	0.7	0.5	1.0
Apatite	1.1	0.5	0.3
Rutile	0.9	0.0	0.0
Augite	0.0	0.2	0.0
Total count	1011	1679	677

DISCUSSION

Rationale For Distinguishing and Correlating Boulder Layers

The sand from the upper boulder layer in the Gomez Pit and the boulder layers in the Virginia Beach Landfill and City Line Pits are distinguished from the sand from the lower boulder layer in the Gomez Pit and the boulder layers in the Bowers Hill and Yadkins Pits by: 1) Folk (1974) grain size parameters, 2) cluster and principal component analyses of weight percentages of one-half phi sieve fractions, and 3) by heavy minerals. Because of these statistically significant associations, the upper boulder layer in the Gomez Pit and the boulder layers in the Virginia Beach Landfill and City Line Pits are thought to be stratigraphically equivalent and all of these will be referred to as the upper boulder layer. The lower boulder layer in the Gomez Pit and the boulder layers in the Bowers Hill and Yadkins Pits are thought to be stratigraphically equivalent and all of these will be referred to as the lower boulder layer.

The average long, intermediate, and short axes of the the pebbles, cobbles, and boulders are very similar in all boulder layers (Table 4). Due to the variance in the data of the average axis length and that of the maximum projection sphericity, these dimensions can not be used to stratigraphically distinguish between boulder layers.

Characterization of The Upper and Lower Boulder Layers

The sand deposited around the cobble to boulder-size clasts in the upper boulder layer is moderately sorted coarse to medium sand (average grain size is 1.26 ∅) that is coarse-skewed (Table 9). This sand contains more kyanite and tourmaline than the lower boulder layer. The lower boulder layer contains a moderately sorted, fine to medium sand (average grain size is 1.83 ∅) that is fine-skewed (Table 9). This stratigraphically older sand contains more epidote, garnet, and zircon than the upper boulder layer sand (Table 8).

Source of Boulders

The rock types are very similar in both of the boulder layers (Table 2). The lithologies reflect their possible origins in the Valley and Ridge, Blue Ridge, and Piedmont Provinces of the Appalachians and more specifically, in the drainage basin of the James River. The Valley and Ridge Province consists of sedimentary rocks varying in age from Cambrian to Mississippian. The lithologies are principally limestone, dolostone, shale, sandstone and small amounts of quartzite and conglomerates. The Blue Ridge Province is a complex of Pre-Cambrian to early Cambrian igneous and metamorphic rocks. Rock types include monzonite, granodiorite, biotite gneiss, schist, syenite, anorthosite, diorite, unakite, graywacke, phyllite, and quartzite (Milici et al., 1963). The Piedmont Province is an assemblage of igneous and metamorphic rocks of

Table 9. Average statistical parameters of the sands within the boulder layers.

Location	Mean	Sorting	Skewness	Kurtosis
Gomez Pit Upper Boulder Layer	1.16	0.97	-0.07	1.26
City Line Pit	1.41	1.03	-0.21	1.22
Va. Beach Landfill	1.22	0.78	0.15	1.34
Average Upper Boulder Layer	1.26	0.92	-0.04	1.27
Gomez Pit Lower Boulder Layer	1.93	0.71	-0.006	1.27
Bowers Hill Pit	1.95	1.15	0.01	1.21
Yadkins Pit	1.62	1.10	0.32	0.94
Average Lower Boulder Layer	1.83	0.99	0.11	1.14

uncertain age along with shale and sandstone in Triassic basins. Granite dominates the igneous rocks, while the metamorphic rocks include gneiss, schist, and phyllite. Small amounts of greenstone volcanics, hornblende gabbro, and quartz diorite are also found in this province (Milici et al., 1963).

Quartzite dominates the lithologies in the boulder layers, comprising approximately 78 percent of the clasts. The probable origin of the quartzite is from the Cambrian Chilhowee group near the boundary between the Valley and Ridge and Blue Ridge Provinces or from the Lynchburg Formation in the Blue Ridge. The quartzite boulders are usually white to gray in color and the grains within these clasts are usually well sorted. Quartzite clasts containing scolithus burrows are common in all boulder layers.

Sandstone and siltstone account for 7.8 ± 1.1% of the rock types in the boulder layers. The probable origin of these lithologies might be the Triassic basins in the Piedmont Province rather than the Valley and Ridge Province due to the high percentage of sandstone boulders at the sampling site in the James River immediately downstream of the outcrop area of these Triassic sandstones (Table 3). The James River cuts across 16-17 kilometers (10-11 miles) of Triassic rocks in the Richmond Basin west of Richmond. This basin might be the source of the sandstone cobbles in the James River. The reason sandstone and siltstone represent only 7.8% of the lithologies in the boulder layers and 54% in the James River samples is probably due to the lack of resistance to abrasion and breakage in fluvial transport of sandstone relative to quartzite (Plumley, 1948). Sandstone might be broken up in transport before it could be deposited in the boulder layers despite the fact that these sandstones are quartz cemented.

Granite comprises 4.9 ± 0.9% of the clasts in the boulder layers. In the James River, granite comprised only one percent of the rock types. This difference might be due to outcrops of the Petersburg Granite downstream of Richmond and the area sampled in the James River. Granite clasts are usually the largest boulders found in the boulder layers, some with long axis lengths over 1.5 meters. Similar size clasts weather-out of Petersburg Granite exposures along the James River.

Schist, gneiss, and greenstone comprise 6.3 ± 1.0% of the lithologies in the boulder layers. Gneiss made up 7.2 ± 2.4% of the rock types in the James River samples, schist and greenstone are absent in these samples. These boulders probably originated from the Piedmont Province.

Unakite accounts for 1.4% of the rock types in the boulder layers. Unakite probably originated in the Blue Ridge Province in the Pedlar Formation or near the contact of the Virginia Blue Ridge complex with the greenstone of the Catoctin Formation (Nelson, 1962).

The James River is the probable source river for the boulders found in the boulder layers in southeastern

Virginia. The mouth of the James River is geographically close to the boulder layer deposits and it drains lithologies which are similar to the rock types in the boulder layers.

The heavy minerals might indicate the provenance for the sands within the boulder layers. These minerals reflect their origin within the Valley and Ridge, Blue Ridge, and Piedmont Provinces of Virginia. Hornblende and epidote are the dominant minerals in each pit. Hornblende comprises approximately 46% of the heavy minerals in the boulder layers. Epidote represents 28.5 ± 1.1% of the heavy minerals in the lower boulder layer and 22.3 ± 1.6% in the upper boulder layer. Hornblende is an important and widely distributed heavy mineral in igneous and metamorphic rocks, being commonly in syenite and diorite (Hurlbut, 1971). Both of these lithologies are present in the Blue Ridge Province, but are absent in the boulder layers. Hornblende is also found in schist, gneiss, and granite, which are found in the Blue Ridge and Piedmont Provinces as well as in the boulder layers. Epidote is often formed during the metamorphism of impure limestone and is characteristic of contact metamorphism (Hurlbut, 1971). A probable source of the epidote in sands within the boulder layers might be from marble in the Evington Group in the Piedmont Province. The James River cuts across approximately 87 kilometers (54 miles) of outcrops from this Group. Epidote is also found in schist, which is in the Piedmont Province.

Garnet is found in metamorphic and igneous rocks, but is especially characteristic of metamorphic rocks (Hurlbut, 1971). Garnet commonly forms in mica schist, hornblende schist, and gneiss (Hurlbut, 1971), which are present in the Blue Ridge and Piedmont Provinces. Garnet makes up 11.6 ± 0.8% of the heavy minerals in the sands within the lower boulder layer and 10.1 ± 1.0% in sands of the upper boulder layer.

Kyanite comprises 5.7 ± 0.6% of the heavy minerals in the sands of the lower boulder layer and 10.4 ± 1.0% in the upper boulder layer. Kyanite commonly occurs in metamorphic schist and gneiss, but never occurs in igneous rocks (Kerr, 1959). The Blue Ridge and Piedmont Provinces contain both schist and gneiss which might contribute kyanite to the boulder layer sands.

Tourmaline makes up 1.7% of the heavy minerals within the sands of the lower boulder layer and 5.3 ± 0.8% in the upper boulder layer. Tourmaline commonly occurs in granite pegmatites, gneiss, and schist (Hurlbut, 1971). Both the Blue Ridge and Piedmont Provinces contain these lithologies.

Wollastonite comprises 1.8% of the heavy minerals in sands of the lower boulder layer and 2.4 ± 0.4% of the sands in the upper boulder layer. This mineral occurs as a contact metamorphic mineral in limestone (Hurlbut, 1971). Marble in the Evington Group in the Piedmont Province might be the source of wollastonite.

Though some of the heavy minerals have their origin in either igneous or metamorphic sources, nine of the thirteen heavy minerals identified in the sands of the boulder layers are commonly associated with high rank metamorphic sources (Table 10). Of the four remaining heavy minerals not included in the list with metamorphic sources (spinel, wollastonite, rutile, and augite) in Table 10, only augite is not associated with metamorphic sources. Augite is commonly associated with dark colored igneous rocks (Hurlbut, 1971). Spinel, wollastonite, and rutile are associated with either gneiss, schist, or metamorphic limestone (Hurlbut, 1971). Twelve of the thirteen heavy minerals identified in sands of the boulder layers are associated with medium grade metamorphic rock sources. Hornblende and epidote make up approximately 70% of the heavy minerals found in the sands of the boulder layers, the source rocks of these minerals indicate metamorphic and igneous origins. Schist, gneiss, and granite are the common source rocks of hornblende and metamorphosed limestone and schist are the common sources of epidote.

The most probable source of the heavy minerals within the sands of the boulder layers would be the medium and high rank metamorphic regions of the Blue Ridge and Piedmont Provinces in Virginia. Several of the heavy minerals (spinel, rutile, epidote, and wollastonite) are associated with metamorphism of impure limestone and might indicate a possible source in the Evington Group of the Piedmont

Table 10. Provenance of some typical heavy minerals (Carver, 1971).

Reworked sediments	Well-rounded grains of rutile, tourmaline, zircon.
Low-rank metamorphic	Biotite, chlorite, spessartite garnet, tourmaline (especially small, euhedral, brown crystals with graphite inclusions).
High-rank metamorphic	Actinolite, andalusite, apatite, almandine garnet, biotite diopside, epidote, clinozoisite, glaucophane, hornblende (including blue-green varieties), ilmenite, kyanite, magnetite, sillimanite, sphene, staurolite, tourmaline, tremolite, zircon.
Sialic igneous	Apatite, biotite, hornblende, ilmenite, monazite, muscovite, rutile, sphene, tourmaline, zircon.
Mafic igneous	Augite, diopside, epidote, hornblende, hypersthene, ilmenite, magnetite, olivine, oxyhornblende, pyrope garnet, serpentine.
Pegmatites	Apatite, biotite, cassiterite, garnet, monazite, muscovite, rutile, tourmaline (especially indicolite).
Ash falls	Euhedral crystals of apatite, augite, biotite, hornblende, and zircon.
Authigenic	Hematite, leucoxene, limonite, tourmaline, zircon; euhedral crystals of anatase, brookite, pyrite, rutile, and sphene.

Province. The Arch Marble, a fine grained highly impure marble, is a possible source of these minerals. Schist and gneiss are common source rocks for nine of the heavy minerals, these lithologies are common in the Blue Ridge and Piedmont Provinces in Virginia.

Cluster analysis of heavy mineral data from the sands within the boulder layers (Figure 13) separates the upper boulder layer from the lower boulder layer. The upper boulder layer contained more kyanite and tourmaline, whereas the lower boulder layer contained more epidote, garnet, and zircon (Table 8). These differences were insufficient to propose a different provenance for the upper and lower boulder layer sands.

Depositional Environment of The Boulder Layers

The lower boulder layer is associated with a channel deposit cut into the Chowan River Formation in the southern portion of the Gomez Pit. The boulder layer is a nearly horizontal layer at the top of the channel deposit and only within the boundaries of the channel in this pit (Figure 10). The Chowan River Formation in the Gomez Pit is present as fossiliferous sands and silts containing Argopecten, abundant Glycymeris subovata along with some Ostrea and Noetia.(Table 6).

Tree stumps are in life position over the lower boulder layer in the Gomez Pit and the Tidewater Sand Company Pit. The tree stumps are usually encased with mud, thus helping to preserve them. The roots of these in-place tree stumps commonly entwine the boulders directly below them. The tree stumps represent a period of subaerial exposure after the deposition of the lower boulder layer. The duration of this period was long enough to allow for the trees to grow to full size; 20-50 years could be enough time for this to occur. Swift (1968) described a possibly analogous situation in the Bay of Fundy and on the southern coast of Florida, where a "drowned forest" was created when the trees were killed by salt water as sea-level rose during the Holocene. When the trees were at the landward edge of a marsh, the stumps could be buried by marsh deposits and preserved (Swift, 1968). Though the "drowned forest" described by Swift did not overlie a boulder layer, it does describe a process by which the in-place stumps over the lower boulder layer might have been preserved.

The assemblage of foraminifers within the sands of the lower boulder layer in the Gomez and Yadkins Pits and in the sands of the upper boulder layer in the Gomez Pit indicates lagoonal, nearshore, or inner shelf environments for the deposition of the boulder layers (Murray, 1973) (Table 1, Appendix F).

A Crassostrea virginica layer is found immediately above the upper boulder layer in the Gomez Pit and above a herringbone cross-bedded and mud draped sand which overlies the boulder layer in the City Line Pit. These overlying deposits indicate estuarine or tidally influenced lagoonal environments. Between the upper and lower boulder layers in this pit there are occasional fine, pasty mud deposits with C. virginica, Mercenaria mercenaria and Mytilus edulis along with abundant plant debris and organic matter (Darby, 1983). These are possibly marsh deposits dissected by medium to coarse sand-filled channel deposits or mud-filled channels cutting sandy tidal flats. Both possibilities occur based on the configuration of these mud and sand deposits in the Gomez, Tidewater Sand Company and City Line Pits (Darby, 1983; Jasper, 1982). Regardless of whether the environment was a marsh or a tidal flat, the environment of deposition from above the lower boulder layer to immediately above (0.5-2.0 meters) the upper boulder layer in all of the pits is that of an estuary or lagoon. The occurrance of nearly the same depositional environment relative to sea-level both below and above the upper boulder layer along with the previously established transgressive sequence of estuarine to bay to beach sediments overlying the upper boulder layer (Darby, 1983; Jasper, 1982) argues for a single transgressive depositional sequence for the sediments above the lower boulder layer.

Some boulders in the upper boulder layer were used as a substrate for C. virginica, and a few clasts have worm tubes on them. This colonization directly upon the upper boulder layer in addition to the foraminifers and C. virginica indicates that the boulders in this layer were exposed to lagoonal or shallow marine environments and probably occassional storm waves after they were deposited.

Long axis of cobbles and boulders might be oriented parallel or perpendicular to currents or wave orthogonals. Long axis orientations on shorelines are usually parallel to the shoreline, normal to the direction of swash and backwash (Krumbein, 1939; Blatt et al., 1980). Long axis orientations in the upper boulder layer in the Gomez Pit and in the City Line Pit show a northeast-southwest trend (Figure 11, Appendix D). The boulders in the Yadkins Pit, the only location in which the lower boulder layer has a perferred long axis orientation, show an east-west preferred orientation (Figure 11, Appendix D).

After the boulders were deposited in the boulder layers, they might have been reworked by storm currents or waves of a transgressing sea. The long axes would be oriented to reflect the orientation of the shoreline at that time.

Dip directions might be caused by water currents moving over a boulder and eroding sand on the down current side of the boulder by separation turbulence around the boulder. Cobbles and boulders along a shoreline usually dip towards the sea (Reineck and Singh, 1975), but the dip direction can vary, having a direction towards the sea or towards land depending on the position of the clast along the shoreline (Reineck and Singh, 1975; Blatt et al., 1980). The perferred dip directions of the lower boulder layer in the Gomez Pit, the upper boulder layer in the Gomez Pit, and the City Line Pit show a general southern trend. This would be consistent with the general current trends generated from a Northeastern Storm today.

Mode of Transport For The Boulders

Fluvial transportation, river-ice rafting, and tree-root rafting are the three different proposed means by which the boulders might have been transported from the Valley and Ridge, Blue Ridge, and Piedmont Provinces to southeastern Virginia. Tree-root rafting appears to be the least feasible of the three, because of the limited availability of boulders now seen in tree roots along river banks like the James River today. A long period of time with no net deposition would be needed to accumulate the quantity of boulders found in these layers. While boulder layers are found deposited on ferricrete and more compact horizons, they also occur without associated diagenetic, compaction or even textural changes from below to above the cobbles or boulders. Although this does not preclude a hiatus, the likelihood of one which would allow slow deposition of cobbles is diminished by the absence of a consistent sharp contact at boulder layers throughout the study area. Because this period of no net deposition of sediments is unlikely, an erosional or winnowing interval would be required to remove the sediments deposited concurrent with slow accumulation of tree-rafted clasts and concentrate these clasts into layers. Again, the absence of a sharp contact beneath every boulder layer deposit argues against such an erosional event but does not preclude it. In addition, large boulders with long axis lengths up to 2.5 meters might be difficult to transport in tree roots over long distances although Hanretty (1974) calculated the feasibility of such an event.

Fluvial transportation of the clasts in the boulder layers is a more feasible means of transportation than tree-root rafting. Evidence in favor of fluvial transportation of the clasts in the boulder layers are abundant rounded and well rounded clasts, occassional broken rounds, a high percentage of boulders with crescentric impact marks, and abundance of durable lithologies, such as quartzite, and a decrease in less durable lithologies such as sandstone relative to quartzite from upstream of Richmond to the Coastal Plain (Table 3).

Assuming that the estimated drop in sea-level prior to Sangamon time was approximately 100 meters (300 feet), a shear velocity was calculated for the ancestral James River based on its probable slope during this low stand of sea-level. The average slope of a paleochannel between the fall line near Richmond, Virginia and the boulder layers during a time of glacio-eustatic sea-level lowered by 100 meters is 0.00084. This was the largest slope determined by using the straight-line distance between Richmond, Virginia directly to the boulder layers in the Coastal Plain. Using the actual course of the present James River valley would yield a slope of 0.00059. In order to account for the larger clasts, the larger slope will be used in the evaluation of fluvial transport for the boulders to their present location in the Coastal Plain.

The estimated depth of the ancestral James River used in the following calculation was 8.7 meters (28.6 feet). This was the maximum depth of the James River recorded on modern flow records near Richmond. The shear velocity (U_*) calculated for these conditions using $U_*=\sqrt{gDS}$ (Blatt et al., 1980) was 26.8 cm/sec. Maximum particle diameter which could be moved or entrained by this shear velocity is nine centimeters (Shields Diagram). If the depth was increased by 50%, the shear velocity would increase to 32.9 cm/sec. The largest particle this shear velocity could entrain is ten centimeters. Doubling the flow depth did not effectively increase the size of clasts which could be entrained.

The average size of the clasts in the boulder layers, eight centimeters, could be entrained under present flood conditions (D=8.7 m, U_*=26.8 cm/s) in the James River near Richmond. However 27% of the clasts found in the boulder layers are larger than nine centimeters. Shear velocities with a 50% increase in depth (13.1 meters) could entrain particles only up to ten centimeters and 21% of the clasts in the boulder layers are larger than this size. Thus paleo-flood conditions using present flood depths and probably over-estimated paleo-slopes for the ancestral James River with sea-level at 100 meters lower than today do not have the capacity to entrain more than 20% of the larger cobbles and boulders found in the boulder layers. In fairness to the proposed fluvial transport of these clasts to their site of deposition in the Coastal Plain, it should be pointed-out that Shields Equation does not adequately account for entrainment of cobble and larger clast sizes. Besides, transient current velocities could exceed those estimated from slope and depth of flow (Middleton and Southard, 1978; Maddock, 1976). Despite these uncertainties another mechanism is probably required to transport at least the largest boulders to their present location.

River-ice rafting provides a plausible means of transporting large boulders (maximum observed size of 2.5 meters) in the boulder layers from the Blue Ridge and Piedmont Provinces in southeastern Virginia. It could also explain the existance of fragile boulders, such as schist, in the boulder layers. The transportation of clasts to the boulder layers by river-ice rafting might occur during extremely cold winters (Darby, 1983). The cobbles and boulders along shallow river channels could be picked up by river ice, which grows downward from the surface of the river, floated downstream during a thaw and deposited near the mouth of the river, estuary or lagoon.

The presence of boulders in the lower boulder layer at the Gomez Pit at the top of a channel fill might suggest a fluvial origin except that the boulders do not occur at the base of the fill as would be expected. In fact the fluvial origin of this channel fill is not certain and there is a good possibility that it is of tidal origin; however, no evidence of crossbedding or other sedimentary structures could be found to resolve its origin. Because the boulders at the top of this channel fill were probably reworked slightly by storm waves, the boulders were more probably originally deposited in the upper part of the channel fill by ice rafting than by fluvial transport.

After the boulders were deposited and reworked, the lower boulder layer was subaerially exposed a short period of time to allow for the growth and development of the trees directly on top of the boulders. These trees subsequently died either from salt water or marsh mud burial due to a transgressive event. Above the lower boulder layer there is approximately two meters (5-6 feet) of medium to coarse sand and some mud filled channels containing paludal fauna (Darby et al., 1984). As the transgression continued the upper boulder layer was deposited by river ice floating into a bay or estuary and dropping the boulders. The foraminifers found within the sands of the boulder layers suggest lagoonal and nearshore environments. Wood debris in small mud-filled channels within the upper boulder layer and some *C. virginica* from the overlying sand which used boulders as substrate suggests that estuarine to lagoonal environment existed before, during and after the deposition of the boulders. The boulders were probably oriented by large storm wave-generated currents in this estuarine or lagoonal environments.

Because a more or less continuous depositional sequence resulting from a single transgression can be interpreted from the base of channel fills cut into the Chowan River Formation and below the lower boulder layer, up through the upper boulder layer and lagoon and bay deposits above (Darby, 1983; Jasper, 1982; Peebles et al., 1984), the probability is reduced for intense winnowing to have occurred for each boulder layer where meters of fluvial deposits would have to be eroded in order to produce a boulder lag. In fact no evidence for such an interval of reworking can be deduce from the evidence presented for the upper boulder layer. Such a reworking would require a dramatic drop in sea-level followed by a subsequent transgression for this upper boulder layer and the continuous nature of the depositional environments argue against such changes.

CONCLUSIONS

Based on field evidence, grain size parameters and heavy mineral analysis of the sands associated with the boulders, the boulder layers in southeastern Virginia can be separated into two similar but distinct layers. The lower boulder layer consists of the boulder layers in the Bowers Hill, Yadkins and Tidewater Sand Company Pits and the lower boulder layer in the Gomez Pit. The upper boulder layer consists of the boulder layers in the Virginia Beach Landfill Pit, City Line Pit, and the upper boulder layer in the Gomez Pit. The lower boulder layer is laterally discontinuous, restricted to the boundaries of a channel fill deposit in the Gomez Pit and similarly interpreted mud-filled channel deposits in the Tidewater Sand Company Pit but of wide spread extend, occurring in pits 16 kilometers (10 miles) to the west. The boulder layers do not appear to merge and are separated by approximately two meters in the Gomez Pit, the only place where both layers are exposed. Boulder size, sphericity, and microfossils are similar in both of the boulder layers.

Boulder lithologies and heavy mineral analysis of the sands within the boulder layers indicate a Blue Ridge and Piedmont provenance. Quartzite, the dominant boulder lithology, probably originated from the Chilhowee group or Lynchburg Formation in the Blue Ridge Province. Hornblende, the dominant heavy mineral in the boulder layers, probably originated from schist, gneiss, and granite sources in the Blue Ridge and Piedmont Provinces of Virginia.

The ancestral James River with sea-level at 100 meters lower than today probably had the capacity to entrain 70-80% of the clasts in the boulder layers; however, it might not have had the capacity to entrain the larger cobbles and boulders found in the boulder layers. Winter river-ice rafting provides a possible means of transportation of the larger and angular boulders and possibly all of the boulders from the Blue Ridge and Piedmont Provinces to the boulder layers in southeastern Virginia. Winter river-ice rafting also explains the presence of fragile boulders in the layers. River ice could pick up the clasts along the shallow reaches of the river channel, float them downstream during a thaw and deposit them near the mouth of the river in an estuary or lagoon.

The continuous nature of the sedimentary sequence indicates that the depositional environments represented by deposits above the lower boulder layer probably would not allow intense reworking of several meters of fluvial deposits necessary to concentrate the boulders in the upper boulder layer into a single layer. This intense reworking would require a drop in sea-level and a second transgression to concentrate the boulders instead of a single transgression as interpreted by this and previous studies (Darby, et al., 1984; Darby, 1983; Jasper, 1982).

REFERENCES CITED

Allen, Rhesa M., 1967. Geology and Mineral Resources of Page County; Virginia Division of Mineral Resources Bull. 81, 78pp.

Blackwelder, Blake W., 1981. Stratigraphy of Upper Pliocene and Lower Pleistocene Marine and Estuarine Deposits of Northeastern North Carolina and Southeastern Virginia. Geol. Survey Bull. 1502-B, 16pp.

Blatt, H., Middleton, G., and Murray,R., 1980. Origin of Sedimentary Rocks, Prentice-Hall, Inc., 782pp.

Carver, Robert E., 1971. Procedures in Sedimentary Petrology, Wiley-Interscience.

Clark, W.B., and Miller, G.L., 1909. A Brief Summary of the Geology of the Virginia Coastal Plain: in Ries, Heinrich, The Clay Deposits of the Virginia Coastal Plain: Virginia Geol. Survey, Geol. Series, Bull. 2, p11-24.

Cronin, T.M., Szabo, B.J., Ager, T.A., Hazel, J.E., and Owens, J.P., 1981. Quaternary Climates and Sea Levels of the U.S. Atlantic Coastal Plain. Science, v. 211:233-240.

Darby, D.A. and Wobus, H.B., 1976. A Versatile Computer Program For Sediment Size Analysis. Tech. Report PSSTR-GE75-25, Old Dominion University, 45pp.

Darby, D.A., 1983. Sedimentology, Diagensis and Stratigraphy of Pleistocene Coastal Deposits in Southeastern Virginia. Fifteenth Annual Virginia Geologic Field Conference, 37pp.

Darby, D.A., Jasper, K.A., and McDaniel,R.C., 1984. Sedimentology of the Mid-Wisconsinan Norfolk Formation: Implications For Sea Level Fluctuations and Barrier Island Genesis: in Field Guidebook for The 11th Annual Shelf and Shore Workshop; editors Kathryn J. Gingerich and Mark Byrnes.

Davis, J.C., 1973. Statistics and Data Analysis in Geology, J. Wiley and Sons, Inc., 550pp.

Emery, K.O., 1955. Grain Size of Marine Beach Gravels. Jour. of Geology, v.63:39-49.

Folk, R.L., 1974. Petrology of Sedimentary Rocks. Hemphills, 170pp.

Hanretty, J. J., 1974. Possible Glacial Erratics in the Pleistocene Norfolk Formation, Virginia Beach, Virginia. Abs., Virginia Jour. of Science, v.25:92

Hurlbut, C.S., 1971. Dana's Manual of Mineralogy, 18th Edition, J. Wiley and Sons, Inc., 579pp.

Jasper, A.K., 1982. Stratigraphy and Depositional Environments of a Late Pleistocene Barrier Island Complex, Southeastern Virginia. Unpubl. M.S. thesis, Old Dominion University, 103pp.

Johnson,G.H., Berquist, C.R., Ramsey, K. and Peebles, P.C., 1981. Guidebook to the Late Cenozoic Geology and Economic Geology of the Lower York-James Peninsula, Virginia. Guidebook No. 3, Dept. of Geology, College of William and Mary, 58pp.

Johnson, G.H. and Peebles, P.C., 1984. The Geological Development of the Lower Chesapeake Bay During the Middle and Late Pleistocene Epoch, in Field Guidebook for the 11th Annual Shelf and Shore Workshop; Editors, Kathryn J. Gingerich and Mark Byrnes.

Kerr, P.F., 1959. Optical Mineralogy. McGraw-Hill Book Company, 442pp.

Krumbein, W.C., 1939. Preferred Orientation of Pebbles in Sedimentary Deposits. Jour. of Geology, 47:673-706.

Kumar, N. and Sanders, J., 1976. Characteristics of Shoreface Storm Deposits: Modern and Ancient Examples. Jour. of Sed. Petology, 46:145-162.

Maddock, T. Jr. 1976. Equations For Resistance to Flow and Sediment Transport in Alluvial Channels. Water Resources Res., v. 12, No.1., p.11-21.

Middleton, G.V., 1965. The Tukey Chi-Squred Test. Jour. of Geology, 73:547-549.

Middleton, G.V. and Southard, J.B., 1978. Mechanics of Sediment Movement. SEPM Short Course No.3, SEPM, Tulsa,OK.

Milici, R.C., Spikes, C.T. and Wilson, J., 1963. Geological Map of Virginia. Virginia Division of Mineral Resources.

Mixon, R.B., Szabo, B.J., and Owens, J.P., 1982, Uranium-Series Dating of Mollusks and Corals, and Age of Pleistocene Deposits, Chesapeake Bay Area, Virginia and Maryland. Geol. Survey Prof. Paper, 1067-E, 18pp.

Murray, J.W., 1973. Distribution and Ecology of Living Benthic Foraminiferids. Crane, Russak and Co., 274pp.

Nelson, W.A., 1962. Geology and Mineral Resources of Albemarle County; Virginia Division of Mineral Resources Bull. 77, 92pp.

Oaks,R.Q. and Coch, N.K., 1973. Post-Miocene Stratigraphy Morphology, Southeastern Virginia. Virginia Division of Mineral Resources Bull. No. 82, 135pp.

Peebles, P.C., Johnson, G.H., and Berquist, C.R., 1984. The Middle and Late Pleistocene Stratigraphy of The Outer Coastal Plain, Southeastern Virginia. Virginia Minerals, 30:13-22.

Plumley, W.J., 1948. Black Hills Terrace Gravels: A Study In Sediment Transport. Jour. of Geology, 56:526-577.

Reeves, R.D. and Brooks, R.R., 1978. Trace Element Analysis of Geological Materials. J.Wiley and Sons, 421pp.

Reineck, H.E. and Singh, I.B., 1975. Depositional Sedimentary Environments. Springer-Verlag, 439pp.

Sanders, J.E. and Kumar, N., 1975. Evidence of Shoreline Retreat and In-Place "Drowning" During Holocene Submergence of Barriers, Shelf Off Fire Island, New York. Geol. Soc. of America Bull. 86:65-76.

Sneed, E.D. and Folk, R.L., 1958. Pebbles in the Lower Colorado River, Texas, A Study in Particle Morphogenesis. Jour. of Geology, 66:114-150.

Swift, D.J.P., 1968. Coastal Erosion And Transgressive Stratigraphy. Jour. of Geology, 76:444-456.

Swift, D.J.P., Heron, S.D. and Dill, C.E., 1969. The Carolina Cretaceous: Petrographic Reconnaissance of a Graded Shelf. Jour. of Sed. Petrology, 39:18-33.

Ward, L.W. and Blackwelder, B.W., 1980. Stratigraphic Revision of Upper Miocene and Lower Pleistocene Beds of The Chesapeake Group, Middle Atlantic Coastal Plain. U.S. Geol. Survey Bull. 1482-D.

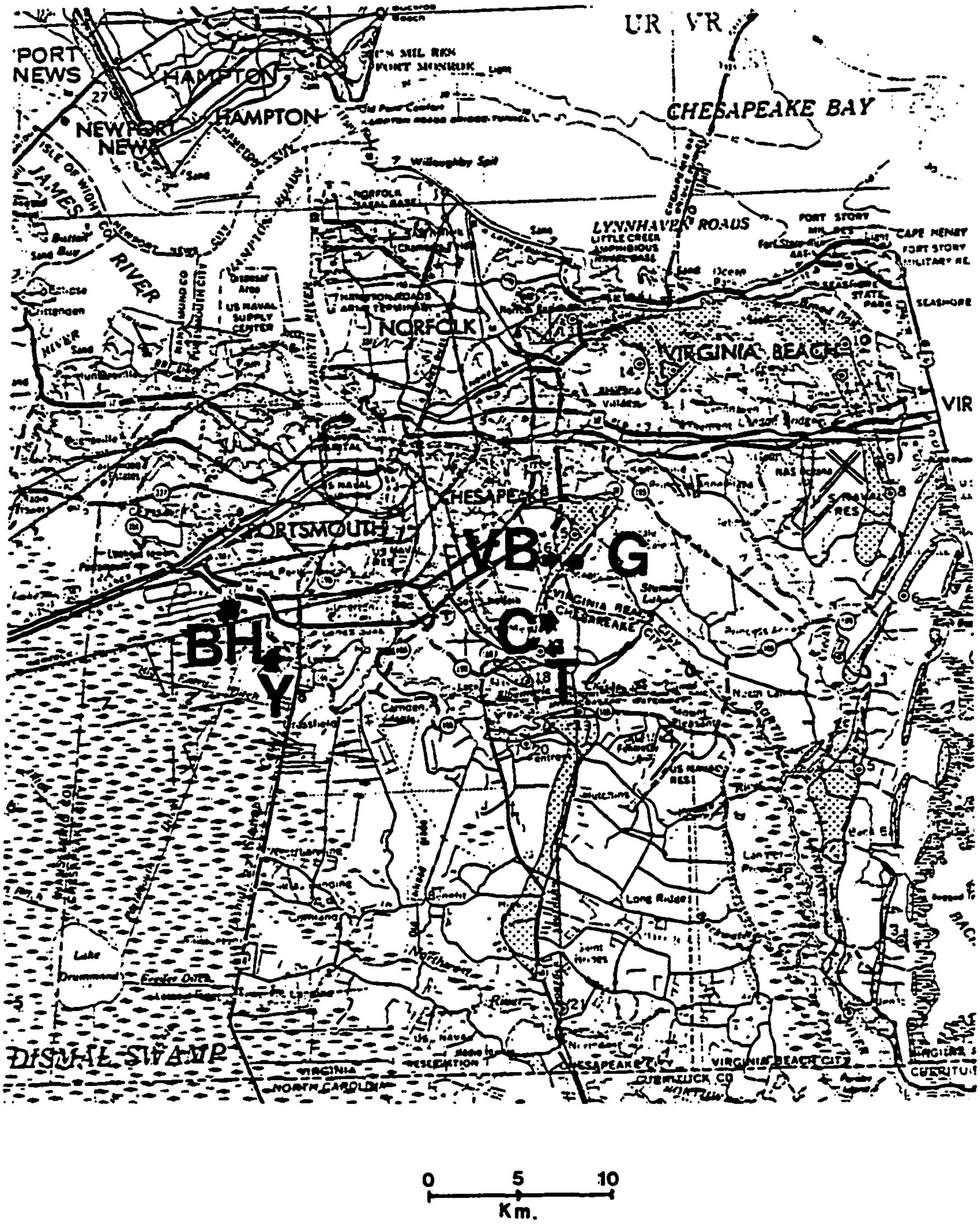
Wentworth, C.K., 1927. Striated Boulders on the Southern Coastal Plain of Virginia. Geol. Soc. of America Bull. 38:150-151.

Wentworth, C.K., 1928. Striated Cobbles In Southern States. Geol. Soc. of America, 39:941-954.

Wentworth, C.K., 1930. Sand and Gravel Resources of the Coastal Plain of Virginia. Virginia Geol. Survey Bull. 32, 146pp.

APPENDIX A

MAP OF SOUTHEASTERN VIRGINIA SHOWING THE LOCATION OF SAND PITS IN WHICH THE BOULDER LAYERS ARE EXPOSED.

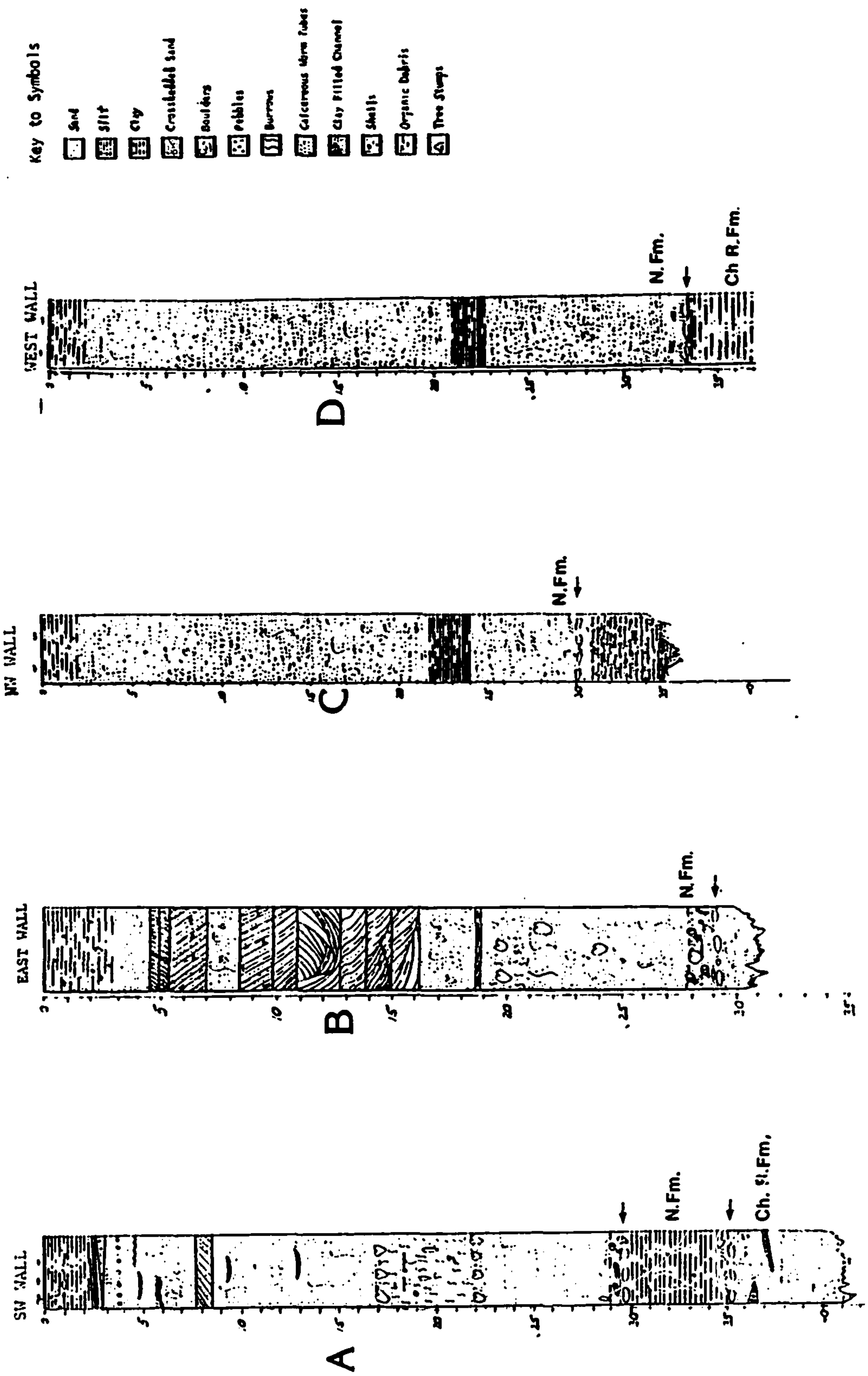


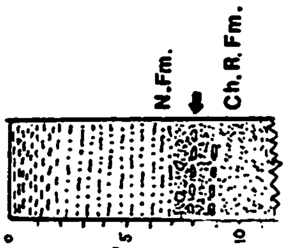
Map of southeastern Virginia showing the location of sand pits in which the boulder layers are exposed (after Force and Geraci, 1975). BH = Bowers Hill Pit, C = City Line Pit, G = Gomez Pit, T = Tidewater Sand Company Pit, VB = Virginia Beach Landfill Pit, and Y = Yadkins Pit.

APPENDIX B

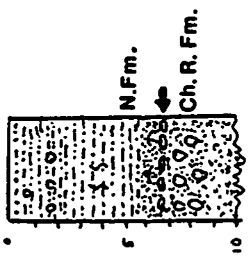
MEASURED SECTIONS CONTAINING BOULDER LAYERS

Measured sections in the Gomez Pit (A), Virginia Beach Landfill Pit (B), City Line Pit (C), Tidewater Sand Company Pit (D), Yadkins Pit (E), and Bowers Hill Pit (F). Arrows indicate the boulder layers in each Pit. The Norfolk Formation (N. Fm.) and the Chowan River Formation (Ch. R. Fm.) are denoted. Depth is in feet below the surface (Jasper, 1982; Darby, unpublished data).


Key to Symbols
Sand
Silt
Clay
WEST WALL
N. Fm.
Ch R. Fm.
D
NW WALL
N.Fm.
C
EAST WALL
N.Fm.
B
SW WALL
N.Fm.
A



F



E

APPENDIX C

LONG AXIS ORIENTATIONS AND DIP DIRECTIONS OF THE BOULDERS

Long Axis Orientations

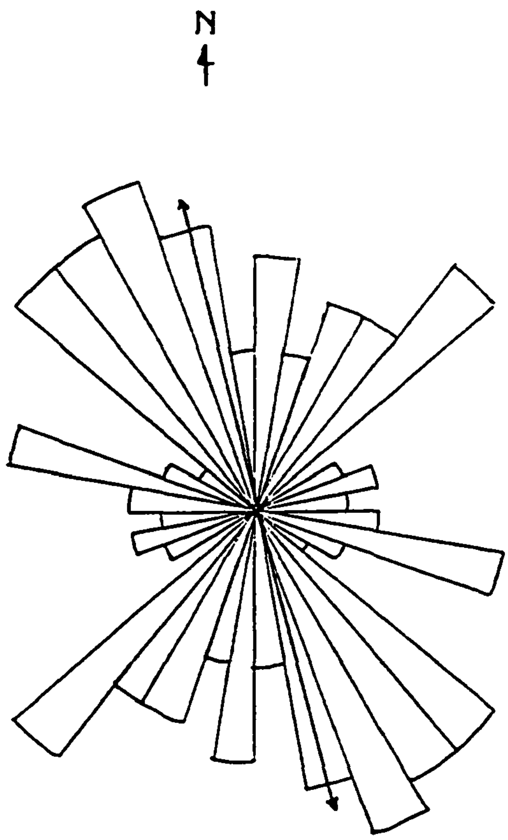
Degrees	City Line Fit	VA. Beach Landfill	Gomez - Upper Boulder Layer	Gomez - Lower Boulder Layer	Bowers Hill	Yadkins
0-10	6	2	8	3	6	1
11-20	2	2	5	3	2	-
21-30	2	3	7	5	-	-
31-40	1	2	7	3	1	2
41-50	3	3	10	3	1	-
51-60	4	1	-	2	2	-
61-70	1	2	3	3	3	1
71-80	2	1	4	3	1	1
81-90	3	4	3	2	6	3
91-100	7	4	4	6	1	1
101-110	8	3	8	2	2	5
111-120	8	4	3	5	1	-
121-130	6	5	2	2	1	3
131-140	8	5	10	6	2	-
141-150	6	1	10	3	1	1
151-160	2	1	11	2	1	-
161-170	7	3	9	3	6	1
171-180	5	6	5	2	1	-

Dip Directions

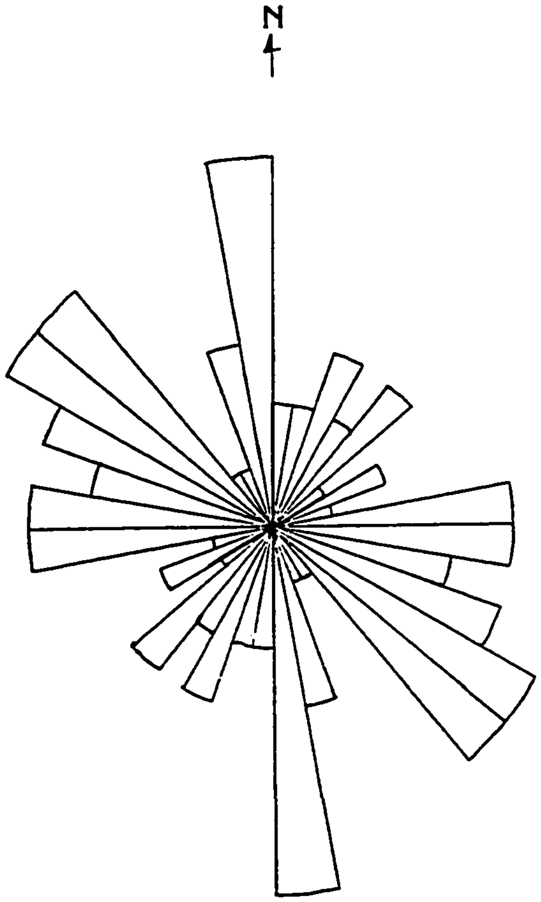
Degrees	City Line Pit	VA. Beach Landfill	Gomez - Upper Boulder Layer	Gomez - Lower Boulder Layer	Bowers Hill	Yadkins
0-10	3	4	4	4	1	2
11-20	1	3	7	5	1	-
21-30	1	1	4	-	-	-
31-40	-	1	1	-	-	-
41-50	-	2	2	-	1	-
51-60	1	-	-	1	1	-
61-70	-	-	-	-	1	-
71-80	-	-	3	-	1	1
81-90	-	-	-	-	4	2
91-100	-	-	-	-	2	1
101-110	1	-	-	-	1	-
111-120	-	-	-	-	-	1
121-130	2	-	-	-	2	-
131-140	1	1	-	2	1	-
141-150	2	1	2	-	1	1
151-160	4	4	5	2	-	-
161-170	7	3	6	6	2	1
171-180	4	4	10	6	-	-
181-190	2	2	5	11	1	-
191-200	11	1	17	7	-	-
201-210	2	1	6	5	-	1
211-220	1	-	8	-	1	2
221-230	3	-	1	1	-	-
231-240	1	-	-	-	-	-
241-250	1	-	1	-	-	-
251-260	1	-	-	-	1	-
261-270	-	-	-	-	3	1
271-280	-	-	1	-	-	-
281-290	-	1	-	-	-	1
291-300	4	-	-	-	-	-
301-310	-	-	1	-	-	-
311-320	5	3	-	2	-	-
321-330	2	2	3	-	-	-
331-340	6	5	6	3	-	-
341-350	3	2	1	1	2	-
351-360	4	8	5	2	-	-

APPENDIX D

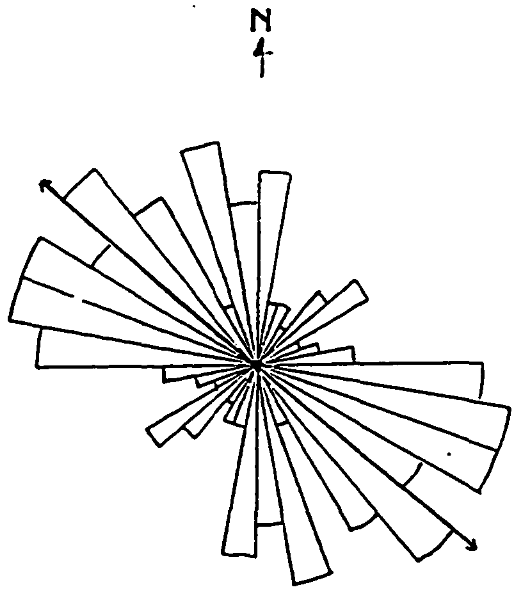
ROSE DIAGRAMS OF LONG AXIS ORIENTATIONS AND DIP DIRECTIONS OF THE BOULDERS



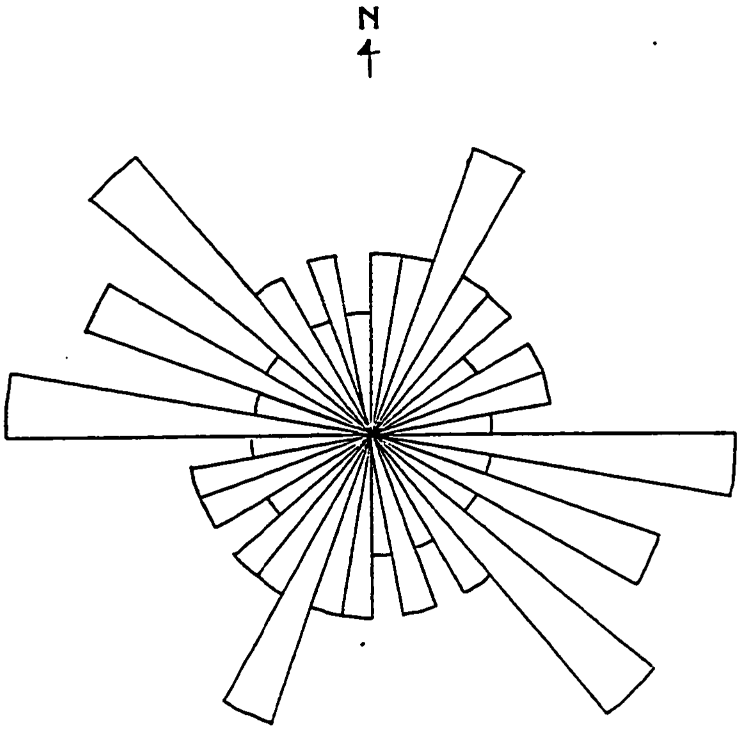
Long Axis Orientations of The Upper Boulder Layer in The Gomez Pit (n=109) Arrow Indicates Preferred Orientation.



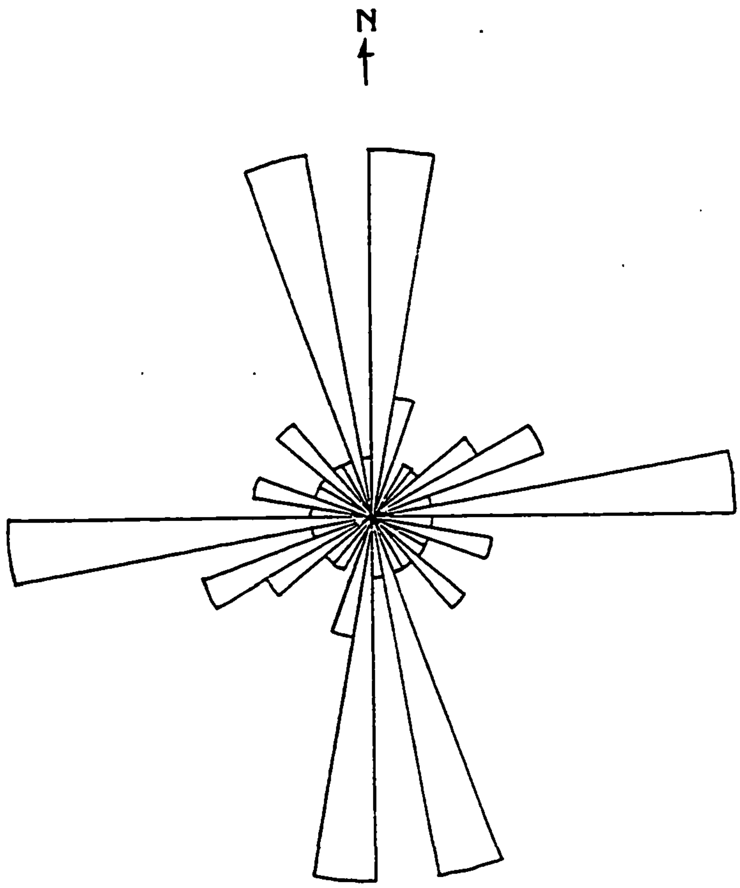
Long Axis Orientations of The Boulder Layer in The Virginia Beach City Landfill Pit (n=52)



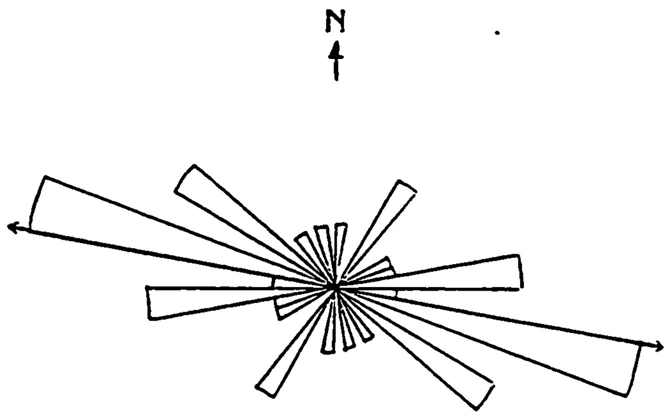
Long Axis Orientations of The Boulder Layer in The City Line Pit (n=81) Arrow Indicates Preferred Orientation.



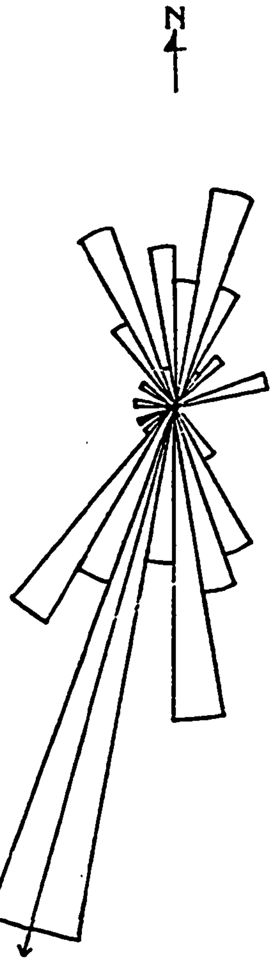
Long Axis Orientations of The Lower Boulder Layer in The Gomez Pit (n=58)



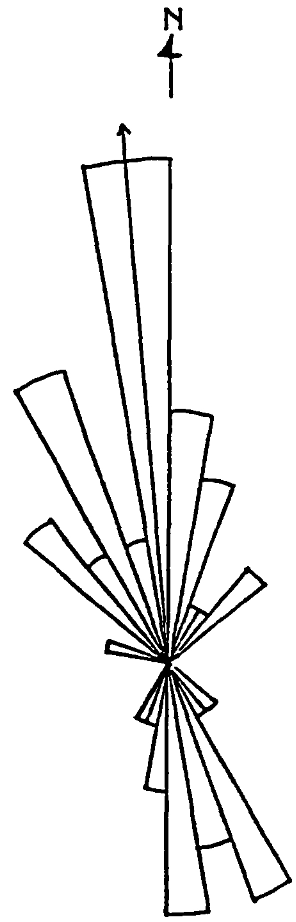
Long Axis Orientations of The Boulder Layer in The Bowers Hill Pit (n=38)



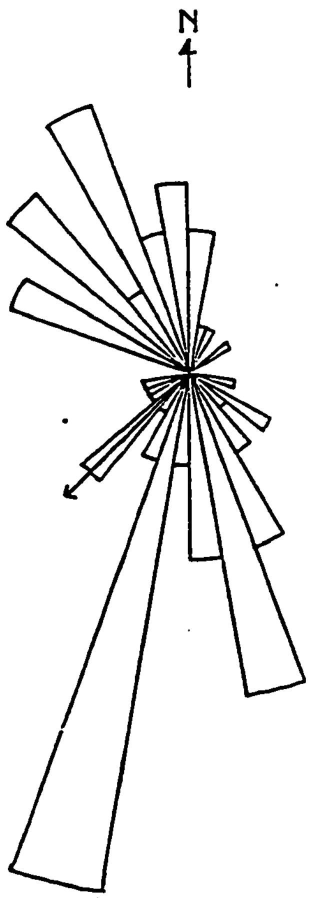
Long Axis Orientations of The Boulder Layer in The Yadkins Pit (n=19) Arrow Indicates Preferred Orientation.



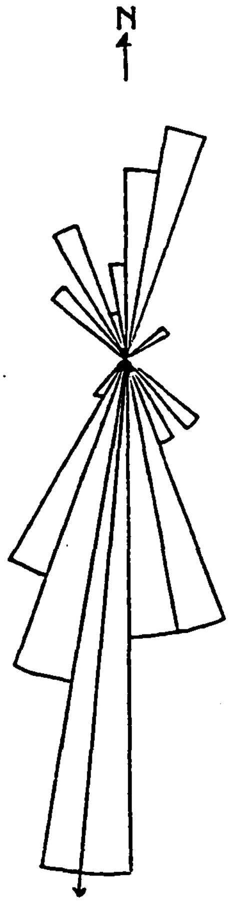
Dip Directions of The Upper Boulder Layer in The Gomez Pit. Arrow Indicates Preferred Orientation.



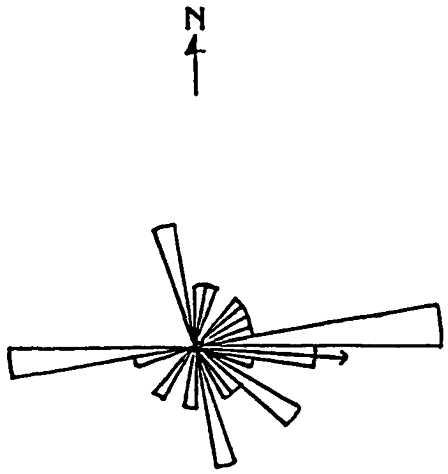
Dip Directions of The Boulder Layer in The Virginia Beach City Landfill. Arrow Indicates Preferred Orientation.



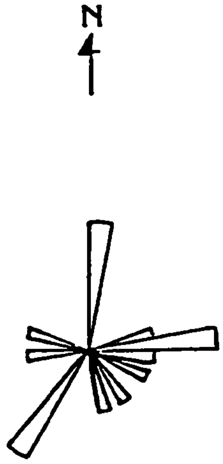
Dip Directions of The Boulder Layer in The City Line Pit. Arrow Indicates Preferred Orientation.



Dip Directions of The Lower Boulder Layer in The Gomez Pit. Arrow Indicates Preferred Orientation.



Dip Directions of The Boulder Layer in The Bowers Hill Pit. Arrow Indicates Preferred Orientation.



Dip Directions of The Boulder Layer in The Yadkins Pit.

APPENDIX E

PLATES

Plates

Plate 1 The upper and lower boulder layers in the Gomez Sand Pit. The upper boulder layer, marked by an arrow in the top right of the picture, is 3.5 meters (11.2 feet) below sea-lèvel approximately 1.4 meters (4.7 feet) above the lower boulder layer. The lower boulder layer, indicated by the lower arrow, is 4.8 meters (15.9 feet) below sea-level. Scale is in ten centimeter increments.

Plate 2 The lower boulder layer in the Gomez Sand Pit, at the base of the Norfolk Formation. Arrows indicate undisturbed boulders encountered in the layer. Scale is in ten centimeter increments.

Plate 3 Edge of the channel associated with the lower boulder layer in the Gomez Sand Pit, marked by the large arrows. The small arrows mark the clasts in the lower boulder layer.

Plate 4 Tree stump in life position above the lower boulder layer in the Gomez Sand Pit. The larger arrows indicate the tree stump and wood debris. The small arrows mark boulders beneath the tree stump.

Plate 5 Upper boulder layer in the Gomez Sand Pit. *Crassostrea virginica* layer is immediately above the boulders, a few *Callianassa* burrows extend into the sand below the boulders on the right side of the photograph. Scale is in ten centimeter increments.

Plate 6 Large granite boulder from the upper boulder layer in the Gomez Sand Pit, long axis length is 0.8 meters. Scale is in ten centimeter increments.

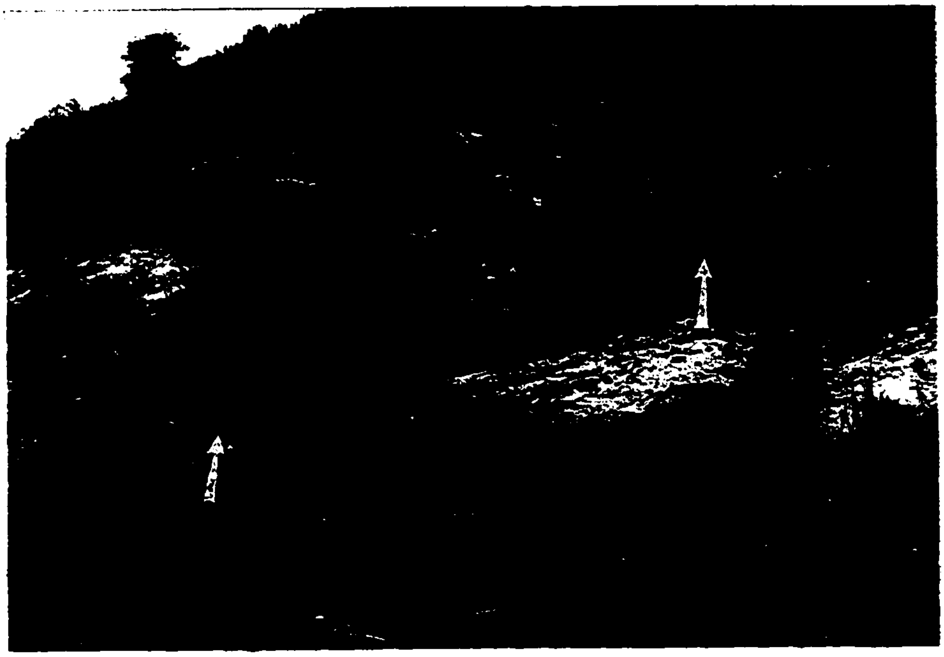
Plate 7 A greenstone boulder from the upper boulder layer in the Gomez Sand Pit, the long axis length is 0.64 meters.

Plate 8 Upper boulder layer in the City Line Pit, 4.4 meters (14.3 feet) below sea-level. The quartzite boulder on the right has a long axis length of 0.39 meters.

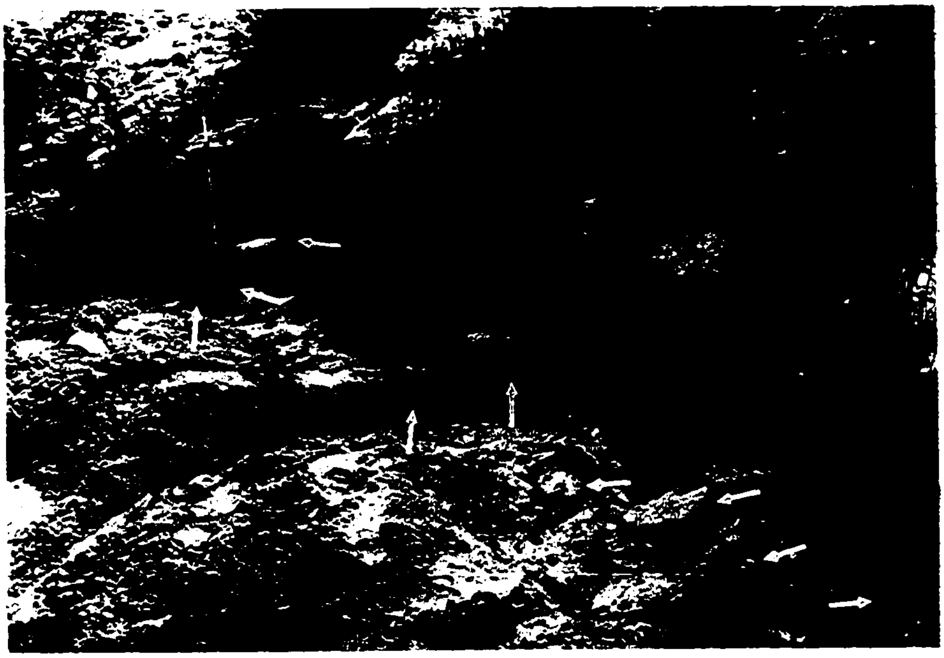
Plate 9 Large gneiss boulder in the upper boulder layer in the City Line Pit. The long axis length is 0.97 meters. Scale is in ten centimeter increments.

Plate 10 Pleistocene boulder layer in the Bowers Hill Pit, indicated by arrows, large mud clasts are above the boulder layer.

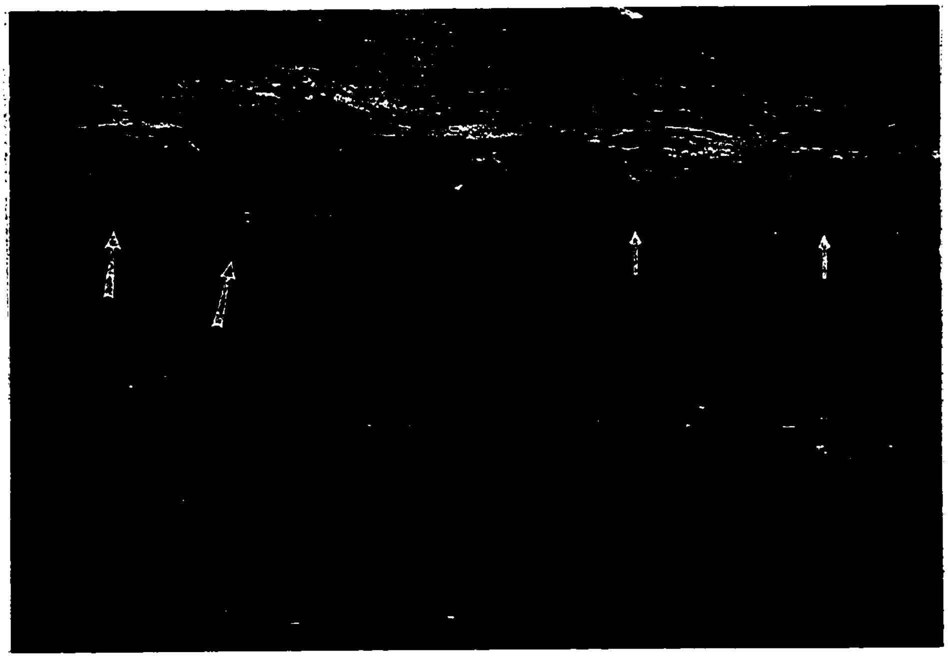
Plate 11 Close up of the Pleistocene boulder layer in the Bowers Hill Pit. The long axis of the large boulder is 0.46 meters.



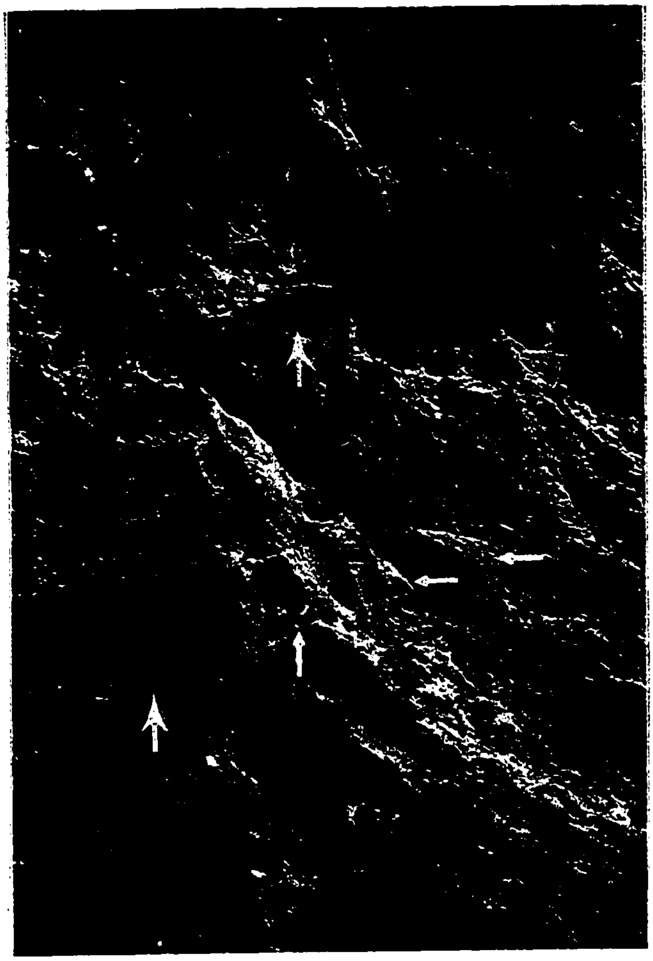
1



2

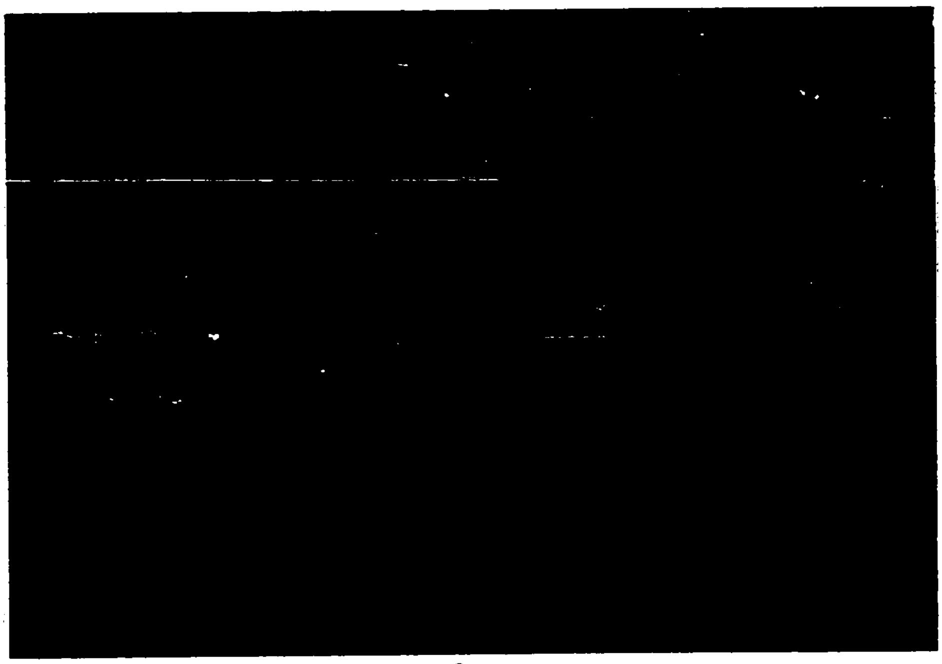


3

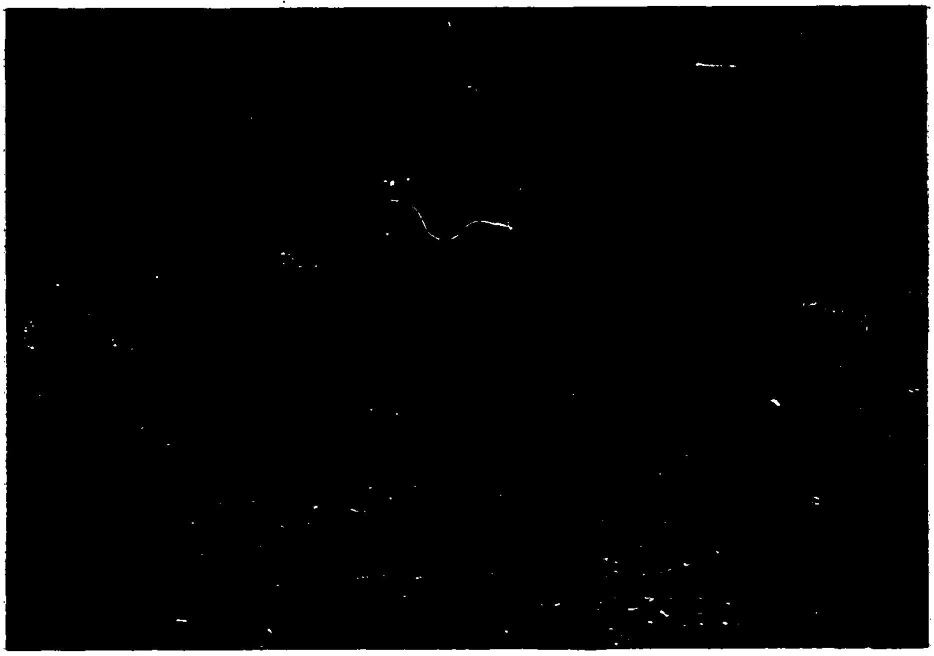


4

5

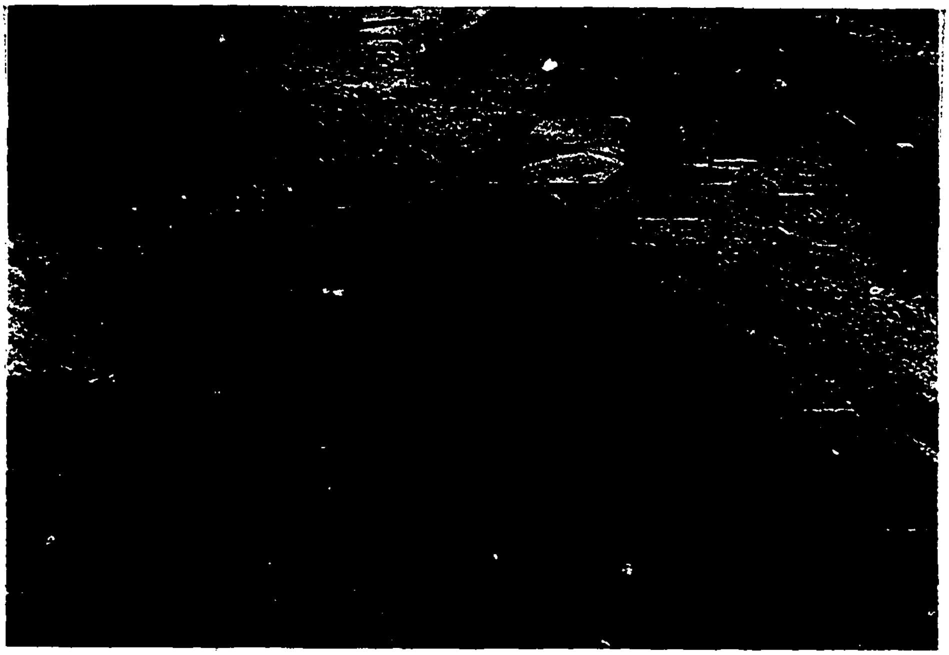


6



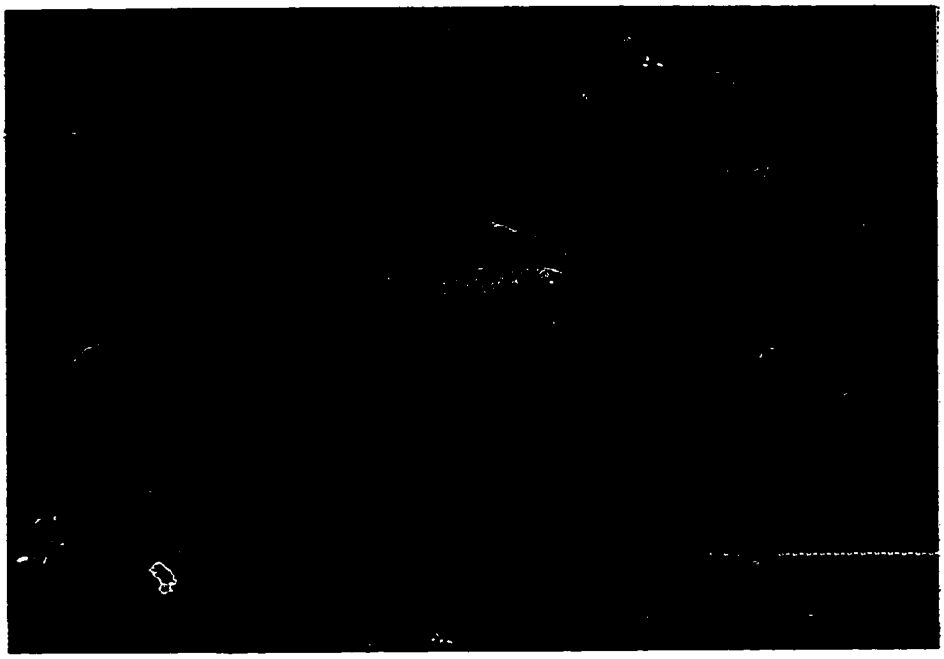
7

8



9

10



11

APPENDIX F

ECOLOGY OF FORAMINIFERS WITHIN THE SANDS OF THE BOULDER LAYERS

Generalized ecology of foraminifers (Murray,1973).
Data given in order of environment, depth, and temperature in which the genera are usually found.

Ammonia- hyposaline and hypersaline lagoons, inner shelf, 0-50 meters depth, 15-30°C.

Buccella- shelf, 0-180 meters depth, cold to warm temperate.

Cibicides- shelf to bathyal, 0- 2000 meters depth, arctic to tropical.

Elphidium- hyposaline to hypersaline tidal marshes and lagoons, nearshore, 0-50 meters depth, 1-30°C.

Nonion- shelf, 0-180 meters depth, cold to tropical.

Nonionella- shelf and bathyal, 10-1000 meters depth, temperate to subtropical.

Quinqueloculina- inner shelf, normal marine and hypersaline lagoons, 0-40 meters depth, mainly temperate to tropical.

Rosalina- inner shelf, 0-100 meters depth, temperate to subtropical.